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Promoting global CCS RDD&D by stronger U.S.–China collaboration

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ABSTRACT

Carbon capture and storage (CCS) is the only technology available to mitigate greenhouse gas (GHG) emissions from large-scale fossil fuel usage. U.S. and China are the world's largest GHG emitters. Collaboration between the two nations, therefore, offers the greatest opportunity for achieving meaningful reductions in global GHG emissions. Two countries' current cooperation on CCS through Clean Energy Research Center based on the U.S.–China Strategic Forum on Clean Energy Cooperation mechanism provides an important initial step towards even closer and stronger cooperation in the future. In this paper, we justify such possibility by discourse on the seemly different but complementary social–political context in two countries including political system, government structure, economic policy, national innovation system, energy strategy, and energy market structure. We further address the key elements of future cooperation model by carefully considering the principle of equality and mutual beneficiary, the role of two countries in the whole value chain according to their comparative advantages, and the scale and mechanism of the funding. A milestone for the cooperation until 2030 is drafted and priority areas for both countries in the cooperation are identified. Such cooperation will provide the imperative leadership for global climate change and speed up the global CCS deployment.

Contents

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1. Climate change and CCS

Climate change is a major challenge for the human race. Secure, reliable and affordable energy supplies are needed for economic growth, but increases in the associated carbon dioxide (CO_2) emissions are the cause of major concern. About 69% of all CO_2 emissions and 60% of all GHG emissions are energy-related [1]. However, in the coming decades, fossil energy as coal, oil and natural gas will still dominate the energy mix, which is especially the case for countries like the U.S. and China, two largest GHG emitters in the world. The IEA Energy Technology Perspectives (ETP) projects that the CO_2 emissions attributable to the energy sector will increase by 130% by 2050 in the absence of new policies or supply constraints, largely as a result of increased fossil fuel usage [2].

The only technology available to mitigate GHG emissions from large-scale fossil fuel usage is CCS, though it is still in its infancy. The ETP scenarios demonstrate that CCS will need to contribute nearly one-fifth of the necessary emissions reductions to reduce global GHG emissions by 50% by 2050 as of 2005-year level at a reasonable cost. CCS is therefore essential to the achievement of deep emission cuts. According to the IEA roadmap [3], to realize the projected contribution, from 2010 to 2050, a total of 3400 CCS projects in power generation, industry and fuel transformation sectors, with the capacity to capture over 10 gigaton (Gt) of CO_2 emissions in 2050 and a cumulative storage of around 145 Gt CO_2 is needed. Capture from power generation is projected to represent 5.5 Gt CO_2/year (or 55% of the total CO_2 captured) in 2050. Detailed recommendations on actions and milestone in technology development and deployment, related legal and regulatory system, financing mechanism, public education and engagement, as well as international cooperation are also proposed in report. Especially, to scale up CCS and promote the large-scale deployment as quickly as possible, 100 projects with annual capture capacity of more than 1 million ton need to be implemented before 2020 [3].

Though clear-cut roadmap for CCS development has been figured out, the role of CCS in global energy transition is still controversial. The strongest opposition is that CCS does not make sense because it cannot eliminate but just capture and storage CO_2. Besides, though the main components of CCS are available in different sectors, currently there is no commercially available integration system. Therefore, the large-scale deployment of CCS will inevitably hinder the development of other available options such as wind power and solar power, as well as the future possible technology as hydrogen.

Though there are many novel technologies under laboratory research and it is a must to shift the future energy system from currently carbon-based to decarbonized, they are still in the very early stage of technology development. The experience with the development of major energy technology indicates that it takes at least 40–50 years to mature a novel technology [4]. On the other hand, because of the limit of resource availability and the technology characteristics, currently matured renewable energy technologies like wind and solar are not enough to meet with the increasing energy demand. Therefore the unavoidable though unfavorable reality is that fossil energy will still dominate the energy mix at least until the middle of the century until proven next generation energy technologies scale up.

The Copenhagen climate negotiation is largely unsuccessful and comes to no binding treaty for post-Kyoto global GHG reduction arrangement. Because the immense research and development (R&D) investment requirement for preparing the technology, the high energy and economic penalty, and most importantly the global externality of deploying CCS, its R&D largely lags behind the IEA timetable globally. The global financial crisis since 2008 further diverts the attention of many developed nations and disperses the global climate efforts. An Australian Collaboration [5] study indicates that the global warming is happening faster than human society expects. Hence it is the very time to put aside the controversy and promote global CCS research, development, demonstration and deployment (RDD&D) to fight against the climate change.

Though there are numerous efforts and initiatives in the jurisdiction nation level and dozens of bilateral or multilateral energy cooperation, the scale and urgency of global climate change, as well as the complexity of energy technology R&D indicate that closer international collaboration and stronger leadership are urgently needed, especially in the shadow of financial crisis. Among all the international collaboration, U.S.–China is definitely the most important and promising. The U.S., the top economy power, the most advanced industrialized nation, the biggest energy consumer, the historically biggest GHG emitter and biggest contributor to global GHG inventory, assumes unshakeable responsibility in fight against GHG yet currently is not the signatory of Kyoto Protocol and undertakes no binding GHG cutting obligation. China, the most populous developing country with conspicuous economic growth rate, the current world workshop, the second biggest energy consumer (but biggest coal consumer), the biggest GHG emitter, is a signatory nation of Kyoto Protocol whist undertakes no binding obligation under the principle of "common but differentiated duty". In fact, the difference in the stances of the U.S. and China on climate change is among the most important factors influencing global climate negotiations. From the U.S. perspective, global effort on GHG stabilization without the participation of major developing countries like China and India is destined to be failure. From the China perspective, the current GHG inventory is largely the aftermath of the industrialization process of industrialized countries and GHG mitigation should not hider the social and economic development of developing countries. However, looking through the seemingly differences, a lot of common interests could be identified and lay the firm foundation for closer energy (especially CCS) collaboration between two nations.

The U.S.–China energy cooperation can be traced back to 1979 when two nations established official diplomacy relationship. Currently, in the field of clean coal technology, there is cooperation under mechanism of "U.S.–China Strategic Forum on Clean Energy Cooperation". It is a good starting point, but is not enough and need to be expanded beyond R&D. In this paper, we will argue that closer collaboration on climate change and energy technology (particularly in the case of CCS) is not only in the individual

domestic interest of the U.S. and China. Together, they can provide the critical mass and the momentum to change the energy system globally, and thus have an impact that goes beyond their own jurisdictions. The layout of the paper is as follows: Section 2 will briefly discuss the main stream of CCS technology and the challenges for its large-scale deployment. Section 3 will discuss the global development of CCS, with an emphasis on its status in U.S. and China. Section 4 will justify why stronger U.S.–China collaboration on CCS RDD&D is possible. Section 5 will probe the possible U.S.–China cooperation model, the main elements and the benefits of the cooperation. Section 6 will discuss the possible hurdles and Section 7 concludes.

2. CCS and the key challenges

2.1. Main components of CCS

CCS refers to a set of technologies that can greatly reduce CO_2 emissions from new and existing coal- and gas-fired power plants, industrial processes and other stationary sources of CO_2 [6]. It is a three-step process that includes capture and compression of CO_2 from power plants or industrial sources; transport of the captured CO_2 (usually in pipelines); and storage of that CO_2 in geologic formations, such as deep saline formations, oil and gas reservoirs, and unmineable coal seams. Though CCS is a relatively new concept, technologies exist for all three components. Capture of CO_2 from industrial gas streams has occurred since the 1930s using a variety of approaches to separate CO_2 from other gases. These processes have been used in the natural gas industry and to produce food and chemical-grade CO_2. Existing capture technologies are energy-intensive, and consequently their application to power plants and other industrial sources is expensive. The history of transporting CO_2 via pipelines in the U.S. spans nearly 40 years. Approximately 50 million tons of CO_2 are transported each year in the U.S. through 3600 miles of existing CO_2 pipelines. The injection of CO_2 into oil field for enhanced oil recovery (CO_2-EOR) has been applied in the U.S. and Canada for 30 years. As of year-end 2010, there were 114 CO_2-EOR projects within the U.S. producing 272,000 barrels of oil per day [7]. But injection of CO_2 in EOR is not for sequester purpose and ample geologic formations are needed for storage of CO_2 captured from power plants and other stationary CO_2 sources. Globally, there are only four commercial CCS facilities sequestering captured CO_2 into deep geologic formations and monitoring and verifying that the CO_2 remains sequestered, representing 25 years of cumulative experience on storing CO_2 in deep geologic formations [8].

Capture of CO_2 from power generation represents the biggest potential. Emissions from a total of about 1 000 coal-fired power plants globally were 7.9 Gt CO_2 in 2007, accounting for 27% of total CO_2 emissions. Additional 5900 GW generation capacity is expected to be installed in the coming 25 years in power sector; even with great efforts on clean energy development, at least 50% of them will be fossil based [9]. Capture of CO_2 from power generation can be accomplished by three general methods: pre-combustion CO_2 capture, where carbon is removed from the fuel prior to combustion; oxy-fuel combustion, where coal is combusted in an oxygen and CO_2-enriched environment; and post-combustion CO_2 capture, where coal is combusted normally in a boiler and then CO_2 is removed from the flue gas.

In the post-combustion process, CO_2 is captured from flue gases that contain 4–8% of CO_2 by volume for natural gas-fired power plants, and 12–15% by volume for coal-fired power plants. The CO_2 is captured typically through the use of solvents and subsequent solvent regeneration, sometimes in combination with membrane separation. Separating the CO_2 from this gas stream is challenging because the CO_2 is present in dilute concentrations. In addition, trace impurities in the flue gas can degrade sorbents and reduce the effectiveness of some of the CO_2 capture processes. Also, compressing the captured or separated CO_2 from atmospheric pressure to pipeline pressure (about 2000 psia) represents a large auxiliary power load on the overall power plant system. Though the basic technology (using amine-based solvents) has been used on an industrial scale for decades, the challenge is to recover the CO_2 with a minimum energy penalty and at an acceptable cost. The high capital costs for installing post-combustion separation systems to process the large volume of flue gas is a major impediment to post-combustion capture of CO_2. In spite of these difficulties, post-combustion capture has the greatest near-term potential for reducing CO_2 emissions because it can be retrofitted to existing coal units that generate about 72% of the CO_2 emissions in the power sector [10].

The oxy-combustion process involves the removal of nitrogen from the air in the oxidant stream using an air separation unit or, potentially in the future, membranes. The fossil fuel is then combusted with near-pure oxygen using recycled flue gas to control the combustion temperature. Under these conditions, the primary products of combustion are CO_2 and H_2O, so CO_2 separation is not necessary. In this scenario, CO_2 can be captured from the flue gas by condensing the water followed by compression and storage.

Pre-combustion capture processes can also be used in coal- or natural gas-based plant. In coal-based plant, pre-combustion CO_2 capture is characterized by removing the carbon from the coal prior to utilization in a gas turbine. In this concept, coal is gasified through partial oxidation, using air or oxygen, to produce synthesis gas (syngas), which is composed of hydrogen, carbon monoxide and minor amounts of other constituents including methane. The syngas then passes through gas cleanup stages and a shift reactor to convert the CO to CO_2 and increases the CO_2 and H_2 molar concentrations to approximately 40% and 55%, respectively. The CO_2 then has a high partial pressure and high chemical potential, which improves the driving force for various types of separation and capture technologies. After CO_2 removal, the hydrogen-rich syngas can be fired in a combustion turbine to produce electricity. Additional electricity can be generated by extracting energy from the combustion turbine flue gas using a heat recovery steam generator, in an integrated gasification combined cycle (IGCC) power plant. The CO_2 that is removed is dried and compressed and can be sequestered.

In the parallel, industry process is another significant source of CO_2 emissions. In 2008, the combined CO_2 emissions of five sectors (including the energy conversion or transformation industry as ammonia production or gas processing, biomass conversion, cement, iron and steel and refineries) were 7.4 Gt, accounting about 25% of total global emissions. Much of the most promising short-term potential for CCS – and half of the global economic potential by 2050 – lie in industrial applications, particularly in the developing world [11,12]. In many industry sectors CCS is often the only technology, with the exception of energy-efficiency measures, that allows for deep reductions in CO_2 emissions. The capture technology of CO_2 from high purity industry process like ammonia production or gas processing is available, but many other applications of CCS in industry – for example for boilers, turbines, iron and steel furnaces, and cement kilns – require additional CO_2 separation technologies to concentrate dilute streams of CO_2 to a level that enables economic transportation and storage. In some cases, this capture step requires far-reaching process modifications. Separation technologies include chemical or physical absorption, adsorption, liquefaction or cryogenic separation, and membrane separation. Most involve partial oxidation or full combustion of hydrocarbons. In parallel to capture from power generation, they fall into three categories: removal from diluted streams, similar to post-combustion capture; removal from oxy-fired streams, similar to oxyfuel combustion; pre-process removal, similar to pre-combustion CO_2 capture.

Table 1
Key challenges and RDD&D needs for large-scale CCS deployment.

CO_2 capture	Technology status in 2010	Near-term RDD&D needs 2010–2020	Long-term goals (> 2020)
All technologies	**Availability**: No utility-scale system for power plant and most industrial applications available; Retrofit of CCS technologies unproven **Efficacy**: Industrial facilities will require new sources of heat and power for CCS application; Collection systems for disparate sources on petroleum refineries and LNG production trains. Complex integration and cost issues **Cost**: Prohibitive capital cost; efficiency penalty increases production cost	**Efficiency**: Reduce energy penalty through Process design and heat optimization. Increase operating temperatures and pressures in all boiler and turbine combinations By 2015: Prove technologies at large power plant scale. Identify most effective options for industrial applications: • Identify optimized design to maximize heat and power use in cement kilns and blast furnaces • Prove CHP systems with CCS for fuel transformation facilities • Identify appropriate CCS options for biofuel refineries **Costs**: Reduce capital costs by 10–12%	**Efficiency**: By 2025: • Commercially available systems with > 85% capture rate available for all fuel types • All capture systems, all coals, all firing configurations 45%+, LHV, including CO_2 capture after 2030 By 2030: Commercial pulverized fuel USC boilers operating > 700/720 °C and > 35megapascals (MPa) **Costs**: Reduce capital costs by an additional 10%
Post-combustion technologies	**Availability**: Existing technologies with hundreds of plants in operation around the world in gas processing and chemicals industry. Largely unproven for large-scale flue gas mixtures. No warranties for large-scale combustion application. Technical challenges: • Scale and integration of complete systems for combustion gases • Combustion gas stream composition and solvent	**Availability**: Large-scale plants commercially available for new build and retrofit applications. Warranties offered on proven technologies by 2017. PF-USC plants at ∼25 MPa and 600/620 °C are commercially available **Efficacy:** By 2015: • Prove at commercial scale (> 40 MMscm or c. 4.0 $MtCO_2$/yr in the case of a coal-fired plant) • Prove sustainable solvent usage rates (e.g., hindered amines). Manage corrosion issues • Develop solvents with lower reactivation temperatures to reduce heat requirements for regeneration. Reduce energy penalty to < 8% • Demonstrate integrated systems with flue gas pretreatments and availability > 85% **Costs:** By 2020: • Reduce capital costs by 10– 15% for large-scale systems • Reduce operating costs by 2– 3%	**Availability**: Commercial plant (new and retrofit) with warranties by 2025 for all coal types and CCGTs gas plants. CCS plants with high efficiency PF-USC boilers operating at ∼35 MPa and 700/720 °C are commercially available **Efficacy**: By 2030: • Prove innovative capture options–chemical looping tested for coal and gas
Pre-combustion technologies	**Availability**: Several coal IGCC plants in operation around the world. Several demo projects under development. No integrated system with warranty available **Technical challenges**: Scale and integration for large IGCC plants. Unproven for high availability base load power generation **Costs**: High capital and operating costs	**Availability**: Integrated IGCC CCS plants with high availability and high efficiency turbines for H2 combustion **Efficacy**: By 2015: • Reduce steam requirements for shift conversion. Reduce energy penalty to 7% By 2020: • Prove hydrogen combustion with high efficiency CCGTs	**Availability:** By 2025: • Demonstrate biomass IGCC with physical solvents. Efficacy: Reduce energy penalty to ∼6% • Emergence of commercial systems with gas separation membranes to replace shift converter • Demonstrate novel methods including pressure swing adsorption, electrical swing adsorption and possibly cryogenics **Costs**: Reduce capital costs to be competitive with conventional PF power generation
Oxyfuel technologies	**Availability**: Trials of small scale plants in progress in the power sector (< 30 MW) under development. 250 MW plants proven in blast furnaces **Technical challenges**: High capital and operating costs	• Rotary kiln for oxy-fuel for cement	• Commercial USC combustion operating 30 MPa and temperatures of 600/620 °C by 2025

Table 1 (*continued*)

CO_2 capture	Technology status in 2010	Near-term RDD&D needs 2010–2020	Long-term goals (> 2020)
CO_2 transportation	**Availability**: 50 million tons of CO_2 are transported each year in the U.S. through 3600 miles of existing CO_2 pipelines **Policy challenges**: Legal and regulatory issues related with transportation (including transnational) of CO_2 **Technical challenges**: Uncertainty on the pathway for pipeline expansion; lighter pipeline material and advanced CO_2 compression technologies to lower cost; lack of leak remediation techniques **Cost**: uncertainty about the cost	• Conduct source/sink distribution analysis and perform a country- or region-wide analysis of the optimal layout of a pipeline network • Conduct studies on the design and cost of CO_2 transport via tankers • Improve understanding and knowledge sharing of CO_2 transport leakage scenarios and the effects of impurities on CO_2 pipeline transport • Facilitate the phased roll-out of pipeline network in OECD countries	• Facilitate the phased roll-out of a pipeline network from 2015 to 2025 in non-OECD countries
CO_2 storage	**Availability**: Injection of CO_2 into oil field for enhanced oil recovery (CO_2-EOR) has been applied in the US and Canada for 30 yr **Technical challenges**: Lack of common methodology for CO_2 storage capacity estimation; lack of tools for predicting spatial reservoir and cap rock characteristics; lack of best practice guidelines for storage site selection, operation, risk assessment, monitoring, remediation and closure; uncertain of the impact on health, environment and ecology **Cost**: Uncertainty about the cost	• Work out common global methodology for CO_2 storage capacity estimation and perform a comprehensive assessment of worldwide capacity for CO_2 storage • Develop and revise best practice guidelines for storage site selection, operation, risk assessment, monitoring, remediation and closure • Develop and improve tools for predicting spatial reservoir and cap rock characteristics. Develop safety regulations and criteria for CO_2 storage	

Note: Revised based on [3].

The transportation of CO_2 is a vital component of the CCS process. Even though CO_2 transportation will likely be less costly than CO_2 capture, developing a transportation infrastructure to accommodate future CCS projects may encounter challenges regarding technology, cost, regulation, policy, rights-of-way and public acceptance. However, given that CO_2 pipelines exist today and the similarity of this infrastructure to others that have been developed, such as natural gas pipelines, none of these challenges is expected to be a major barrier to deployment. Pipelines are expected by many to be the most economical and efficient method of transporting CO_2 for future commercial CCS facilities [1,13]. Recent studies have shown that CO_2 pipeline transport costs for a 100 km (62 mile) pipeline transporting 5 million tons per year range from approximately $1–$3 per ton, depending on the factors as distance between the capture and storage points, the terrain the pipeline has to pass through, the anticipated flow rate of CO_2, and population and infrastructure development density [14,15].

The technical community believes that many aspects of the science related to geologic storage security are relatively well understood. However, additional information (including data from large-scale field projects with comprehensive monitoring) is needed to confirm predictions of the behavior of natural systems in response to introduced CO_2 and to quantify rates for long-term processes that contribute to trapping and, hence, risk profiles [1]. CO_2 is not explosive or combustible. Rapid release of CO_2 could, however, damage an injection well during operation and provide a conduit for contamination of underground drinkable water. In addition to risks to drinkable water, injection activities could pose risks to the atmosphere, surface water, human health, ecosystems and the physical environment. While CO_2 is not toxic, direct exposure to elevated levels of CO_2 can cause both chronic (e.g., increased breathing rate, vision and hearing impairment) and acute health effects to humans, animals and vegetation, depending on the concentration and duration of exposure.

2.2. Key challenges and RDD&D needs for the large-scale deployment of CCS

To advance the deployment of CCS as envisioned by the IEA, numerous technical, economic, legal and regulatory issues need to be timely and properly addressed. Most of the technical and economic challenges lie on capture sector. Utility-scale systems coupled with different capture technologies and adapted to different coal property need be demonstrated and significantly improve the operation efficiency. New capture systems need to be developed for industry process (e.g., cement kiln, petroleum refinery) solving process stability and energy penalty issues. System integration and equipment standardization need be realized for low-cost mass manufacturing. On transportation sector, though there are no major technical challenges, lighter pipeline material and advanced CO_2 compression technologies are needed to lower cost and leak remediation techniques need be developed to guarantee the technical feasibility of large-scale transportation. The biggest challenges in transportation are related with policy and regulation: the optimal layout of pipeline network on both national and international levels and the related regulation system. On storage sector, vast body of work on geology survey, best practices on site testing, geology modeling and operation procedures need be carried out: methodology for CO_2 storage capacity estimation in different formulations needs to be developed and field geology survey need be carried out for main regions/countries; best practice guidelines for storage site selection, operation, risk assessment, monitoring, remediation and closure and tools for predicting spatial reservoir and cap rock characteristics need be compiled or invented; the impact of CO_2 on health, environment and ecology system need be properly appraised (Table 1).

3. Global progress of CCS

3.1. Overview of global development

At the end of 2010, a total of 234 active or planned CCS projects have been identified across a range of technologies, project types and sectors [16]. Interested readers please refer to [17,18] for a map of global CCS projects. To verify the technological and economic viability of CCS, commercial scale plants with sequestration annual capacity of more than 1 million ton CO_2 need be constructed and the related operation data need be strictly collected, inspected and verified. Currently, there are only eight commercial scale CCS projects in operation in the world, and all were constructed and put in operation before 2007.

There are another 77 are large-scale integrated projects (LSIPs) at various stages of development. North America accounts for 39 of the 77 LSIPs (31 in the U.S. and 8 in Canada). The allocation of government funding grants to projects is most advanced in this region. More so than in other parts of the world at present, capture projects in North America are seeking additional revenue from the sale of CO_2 for EOR to improve project commerciality. Europe has 21 LSIPs, though projects appear to be moving at a slightly slower pace than in North America. This in part reflects the longer timeframes associated with Europe's key CCS funding mechanism, the NER300 program, as well as uncertain economic conditions. European projects also face significant challenges surrounding the use of potential onshore storage sites, underscoring the need to gain public endorsement for CCS projects. The most advanced CCS activity in Europe is in Norway (which has two operational LSIPs) and in the UK and the Netherlands, with 11 LSIPs under development between them. China is the most active developing country in CCS and there is five identified LSIPs projects, spanning a range of industries from power generation through coal to chemical to oil and gas. Australia has six LSIPs split between the petroleum sector (CO_2 injection projects associated mainly with offshore gas field developments) and projects associated with the capture of CO_2 from power stations and industrial facilities. However there are currently no LSIPs identified in key emitter countries such as Japan, India and Russia.

LSIPs are spread across a number of industries, but of those in development planning the majority (42 projects) are in power generation, reflecting the large allocation of government funding support to that sector. Projects in the cement iron and steel and alumina industries have low representation. By capture technology, pre-combustion and post-combustion capture systems dominate the LSIPs, with 33 and 21 projects, respectively. There are four proposed demonstration projects using oxyfuel combustion (Table 2).

In total, governments have made commitments valued at up to US$40 billion in order to support CCS demonstration projects. Of this, US$11.7 billion has been allocated to specific large-scale demonstration projects. A further US$2.4 billion has been allocated to expand research and development activities. Twenty-two projects account for 87% of funding to all large-scale projects [16]. From both the number of LSIPs and funding, CCS makes encouraging progress globally. However, at this time, it is highly uncertain that whether these funding or LSIPs can be in place as planned. For example, of all the announced projects, only one (the Australian Gorgon project) is proceeding to construction [19]. Whatever, the progress is seriously lagging behind the IEA roadmap and there is a gap on funding between USD 9 and 18 billion [20]. Besides, it is worthwhile noticing that, there has been very little focus on CO_2 capture at industrial facilities, which are expected to make up a significant portion of future CCS projects [21].

Because of the slow move, CCS is still perplexed by immense additional capital investment, as well as high operation cost and energy penalty. Table 3 lists the estimates on the incremental capital investment, the cost of CO_2 avoided and increase in electricity cost by the main sources. The costs associated with investing in, and constructing, large-scale energy projects rose substantially during the latter part of the past decade. CCS technology costs have risen in line with this trend, with recent studies suggesting that costs are 20–30% higher than indicated in similar studies undertaken only two to three years ago. Incorporating CCS into a power plant is likely to increase costs by between 40% and 75% depending on the technology and fuel source. Recent estimates suggest that for a 'reference plant' in the U.S., the average cost of electricity that would need to be recovered overall output for the entire economic life of a generating plant in order to justify the original investment could be in the range of US$120–150/MWh. The associated avoided cost of CO_2 ranges from US$60 to 85/t of CO_2 for coal-based power stations and exceeds US$100/t for gas-fired power plant [16].

Coupled with the failure in global climate policy negotiation, a typical chicken-and-egg problem exists: with no favorable policy

Table 2
List of current integrated commercial scale CCS projects in operation in the world.

Site name	Type	Location	Start date	Cost of CCS (USD)
Weyburn	Capture: coal gasification plant; pro-combustion Transportation: pipeline (330 km) Storage: EOR (2.4 Mt/yr)	USA and Canada (EnCana)	2000	Cap: $127 M ($10.19/tCO_2) Op: 23.6 M ($9.85/t$CO_2$)
Snohvit	Capture: LNG plant; natural gas processing Transportation: pipeline (160 km) Storage: offshore deep saline formation (0.7 Mt/yr)	North sea, Norway	2007	Unknown
Sleipner	Capture: offshore platform; natural gas processing Transportation: pipeline in same site Storage: offshore deep saline formation (1 Mt/yr)	North Sea, Norway	1996	Cap: $106 M Op: $7 M/yr
In Salah	Capture: natural gas processing plant Transportation: pipeline (14 km) Storage: deep saline formation/gas field (1.2 Mt/yr)	Algeria	2004	Incremental cost: $100 M
Salt Creek	Capture: natural gas processing Transportation: pipeline (201 km) Storage: EOR (2.4 Mt/yr)	USA	2006	Cap: pipeline $27 M Total $200 M
Val Verde CO_2 pipeline	Capture: natural gas processing plants Transportation: pipeline (132 km) Storage: EOR (1 Mt/yr)	USA	1998	Pipeline Cap: $27.6 M
Rangley EOR project	Capture: natural gas processing Transportation: pipeline (285 km) Storage: deep saline formation/gas field (1 Mt/yr)	USA	1986	Unknown

Table 3
Estimates of incremental capital investment, CO_2 avoided cost and electricity generation of CCS.[a]

IPCC (2005)	New pulverized coal: cost avoided US$30–70/t$CO_2$; increase in electricity cost: 43–91% New IGCC: cost avoided US$14–53/t$CO_2$; increase in electricity cost: 21–78%
IEA (2008)	US$40–90/t$CO_2$ abated
IEA (2010)[b]	Pilot to large scale: Avg. US$1 billion investment per project over the next 10 yr
IEA (2010)	Post-combustion capture (OECD only) average US$58 with range US$40–69/tCO_2 avoided Pre-combustion IGCC US$43 with range US$29–62/tCO_2 avoided Oxy-combustion average US$52 and range US$27–72/tCO_2 avoided
GCCSI (2009) [67]	Pulverized coal (super and ultra supercritical): US$87–91/t$CO_2$ avoided IGCC: US$81/t$CO_2$ avoided
Bhargava (2010) [68]	Standard coal, no CCS: ~$0.7 M/MWh total costs; US$0.05/kWh Supercritical+CCS: ~US$1.4 M/MWh total costs; US$0.09/kWh IGCC+CCS: ~US$1.6 M/MWh total costs; US$0.11/kWh
Al-Juaied and Whitmore (2009) [69]	First of a kind plant: US$100–150/t$CO_2$ (capture only)
Gao (2010) [70]	IGCC China: incremental capital cost of US$65–106 M (60–100% capture) Expected electricity tariff without incentive: US$94–113/MWh (60–100% capture)
Coal Utilization Research Council[c]	$17.3 B/yr incremental cost for early adopter 45 GW (30-yr plant life) over 20 years $4.5 B/yr incremental cost for pioneer plant 10 GW (30-yr plant life) over 15 yr
Lignite Energy Council	$1 B/yr incremental capital cost for 10 yr for five retrofit and five new demos with storage $3.8 B/yr incremental capital cost for 10 yr for seven integrated projects (> 600 MW)
McKinsey (2008)[d] [71]	New Project: 0.6–1 billion additional cost per plant; US$78–118/t$CO_2$ abated
UK–China NZEC (2009)[e]	IGCC: 0.5 billion; pulverized coal: 0.7 billion; retrofit: 0.9 billion New IGCC China: ~US$42/t$CO_2$ avoided
COACH (2009) [72]	New IGCC China: US$33–40/t$CO_2$ avoided

Note: Sourced from [22].

[a] Current figures are focused on coal-fired power plants unless otherwise stated. CCS projects that include capture from industrial sources such as cement, iron and steel, ammonia and natural gas processing offer lower capture costs because of the high purity of emitted CO_2.

[b] Not specific for developing countries; covers entire project costs, including but not limited to incremental CCS costs.

[c] Angielski, S. and K. Obenshain, 2010. Senator Dorgan CCS Pathways Initiative: Coal Utilization Research Council (CURC) and Edison Electric Institute (EEI) letter to Interagency Task Force on CCS. Online at: 〈http://www.whitehouse.gov/sites/default/files/webform/dorganresponsetaskforce.pdf〉.

[d] Based only on high-level assessment of labor and steel costs in developing countries, which were determined to be 15% less expensive; covers entire project costs, including but not limited to incremental CCS costs.

[e] Covers entire project costs, including but not limited to incremental CCS costs.

in place, investors are disincentive to invest in CCS development and deployment, which incurs the technology remaining immature and expensive; and immature and expensive technology in turn, hinders nations to formulate climate policy to stimulate clean energy development. The aftermath of the vicious cycle is that there leaves less time for the human society to response to the even more serious global warming.

3.2. CCS in the U.S.

In the U.S., CCS RD&D is initiated and promoted by the Department of Energy (DOE). As earlier as 1997, DOE established the Carbon Sequestration Program, which is administered by the Office of Fossil Energy and implemented through the National Energy Technology Laboratory (NETL) to move CCS technologies toward commercialization. The program encompasses all aspects of CCS and has engaged government and private sector partners that have expertise in CCS technology. The program covers three key elements for technology development: core research and development (R&D), infrastructure and global collaborations [23]. The R&D element is driven by industry needs and covers five focal areas (Fig. 1). The infrastructure element includes the Regional Carbon Sequestration Partnership (RCSP) and other small and large-volume field tests in different geologic formation classes where validation of various CCS technology options and their efficacy are being confirmed. The global collaborations element benefits from technology solutions developed in the R&D and infrastructure elements and, in turn, feeds lessons learned into infrastructure and R&D. The feedbacks among three elements provide valuable information and can guide future applied research and development of CCS technologies. Funds from the American Recovery and Reinvestment Act (ARRA) of 2009 were recently utilized by the program to develop CCS technology training centers, conduct additional site characterization studies and to fund small research projects related to CCS. Currently more than 3 billion USD$ is input on CCS RD&D in the U.S.

In the U.S. CCS has long been tied to the politics of coal and fossil fuels, and a CCS research program has often been seen as the cornerstone of that administration's climate policy, which was pursued in lieu of developing any limits on greenhouse gases [24]. CCS was first emphasized during the Bush presidency (2001–2009). The Office of Fossil Energy in the Department of Energy (DOE) and NETL coordinated R&D efforts through research at the National Laboratories and establishment of the RCSP Program. The seven Regional CCS Partnerships, started in 2003, have created regional networks of academics, national laboratories, and private industry in the natural resources and electric sectors, to identify CO_2 sources and sinks and examine regulatory and policy considerations and to conduct research on CCS technologies. The partnerships are currently involved in seven large-scale sequestration demonstration projects (Table 4) throughout the U.S., with each injecting more than 1 million ton of CO_2 [25].

The research networks of CCS in the U.S. evolve around the FutureGen project, a proposed public–private venture to develop a zero-emissions coal-fired IGCC power plant and CCS demonstration project [26]. FutureGen was initiated in 2003 and brought together private companies, which provided 26% of its funding, government funding, and international corporate partners from the coal mining and power sector, including China's largest power company, the Huaneng Power Group, to build the first 275 MW zero-emissions coal-fired IGCC power plant. The plant would be intended to prove the feasibility of producing electricity and hydrogen from coal while capturing and permanently storing carbon dioxide underground. The Alliance intended to build the plant in Mattoon Township, Coles County, Illinois northwest of Mattoon, Illinois, subject to necessary approvals by DOE as part of the National Environmental Policy Act (NEPA) process. However, escalating building costs lead to a new analysis by the DOE estimating that the cost for FutureGen had doubled [27]. Soon

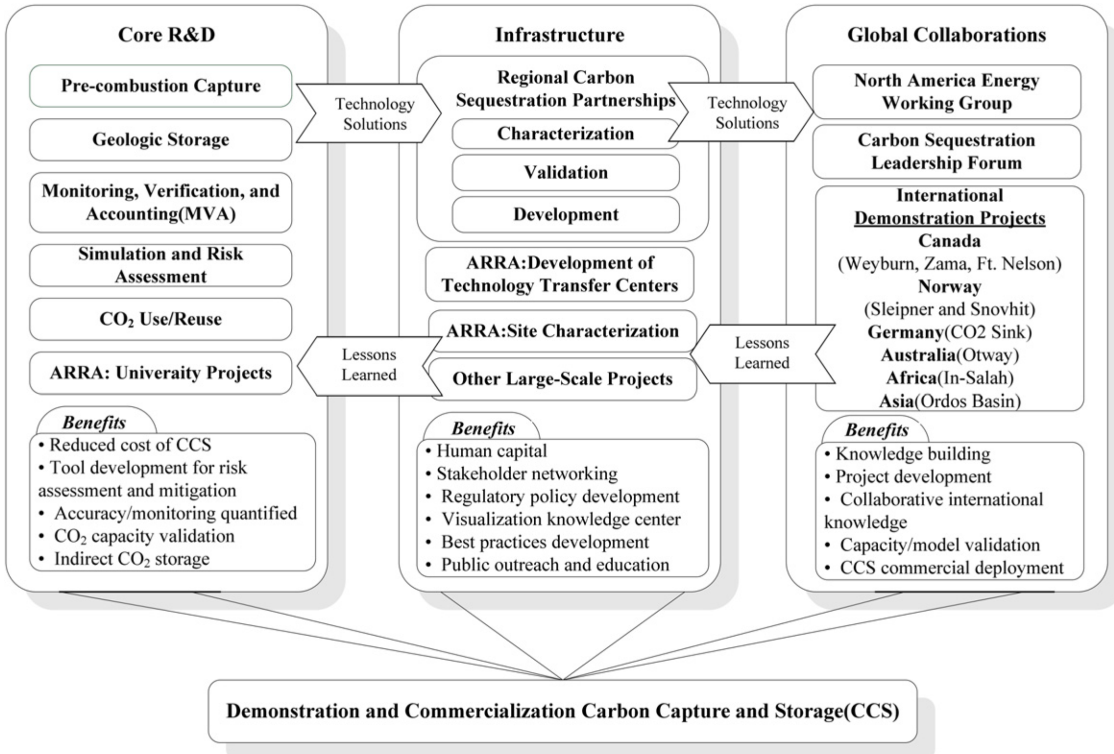

Fig. 1. U.S. DOE Carbon Capture Sequestration Program.

Table 4
CCPI carbon capture demonstration projects in the U.S.

Performer	Location	Capture technology	Capture rate (t/yr)	Start date
Pre-combustion capture				
Summit Texas Clean Energy	Odessa, TX	Selexol	3,000,000	2014
Southern Company	Kemper County, MS	Selexol	2,000,000	2014
Hydrogen Energy California	Kern County, CA	Rectisol	2,000,000	2016
Post-combustion capture				
Basin Electric	Beulah, ND	Amine	500,000–1,000,000	2014
NRG Energy	Thompsons, TX	Amine	500,000	2015
American Electric Power	New Haven, WV	Chilled ammonia	1,500,000	2015
Oxy-combustion capture				
Future Gen2.0	Meredosia, IL	Oxy-combustion	1,000,000	2015

Table 5
Industrial carbon capture and storage intiative projects in the U.S.

Performer	Location	Capture technology	Product	Capture rate (t/yr)	Start date
Leucadia Energy	Lake Charles, LA	Rectisol	Methanol	4,000,000	2014
Archer Daniels Midland	Decatur, IL	Amine	Power, ethanol	900,000	2014
Air products	Port Arthur, TX	Amine	Hydrogen	900,000	2013

after the decision to site FutureGen in Illinois, DOE announced to cancel the project and switch to the scaled-down FutureGen 2.0, which proposes to build an oxy-fueled combustion and CO_2 capture facility with sequestration. Subsequently, several industry partners have dropped out and decided to pursue individual projects, which are now funded under the Clean Coal Power Initiative (CCPI).

In addition to the CCPI program, CO_2 capture demonstration projects are being conducted under the DOE Industrial Carbon Capture and Storage (ICCS) program (Table 5). These projects are pursuing capture technologies that are similar to those being demonstrated for power plants and are of similar magnitude to the CCPI demonstrations. Eleven projects were initially selected for the ICCS program. In June 2010 three projects were selected to move forward to full demonstration.

Though significant progress has been made, there still exist major technical, economic and regulatory challenges to deploy CCS in U.S. First of all, the cancellation of FutureGen IGCC-CCS project indicates that insufficient fund will remain the main

obstacle. Historically, the R&D input on energy technology from both government and industry, has been on shrink ever since 1980s [28,29] (Fig. 2). It is argued that cutbacks in energy R&D are likely to reduce the capacity of the energy sector to innovate. The argumentation is also supported by the conclusion of GAO appraisal on DOE energy R&D that the current level of R&D funding will be insufficient to deploy alternative energy sources in the next 25 years that will reverse the growing dependence on imported oil or the adverse environmental effects of using conventional fossil energy [30]. Field experts argue that 5–10 times of the current energy R&D (ranging 15–30 billion 2005-year USD$) is necessary for the proper energy technology innovations. Though after 2005 the declining trend of public fund for energy R&D was reversed and the 2009 ARRA provided a historically one-off 35 billion $USD appropriation, the national R&D input remains limited. The DOE request for energy R&D in FY2010 and FY2011 ranged between 3.5 and 3.8 billion USD$, approximately equivalent to the actual fund in 2008 [31]. Secondly, favorable policy that can promote the deployment of CCS in the U.S. is still not in place. Federal climate policy legislation has been painfully slow to materialize: the American Clean Energy and Security Act of 2009 (ACES), H.R. 2454, was passed by the U.S. House of Representatives on June 26, 2009, but a parallel bill died in the Senate. If enacted, this legislation would have established a greenhouse gas cap-and-trade program and supported other policies to deploy low-carbon energy technologies [32]. However without clear policy signal, the industry is reluctant to invest in low carbon energy. A recent report on clean energy investment indicates that the rank of U.S. drops from second in 2009 to third in 2010, after China and Germany [33]. Regarding CCS, with the complicated ownership structure of utility and the different institutional structure, as well as the different regulatory and financial environment in states (individual states retain power and responsibility in approving specific CCS projects, managing environmental risk, allowing access to subsurface pore space, and most importantly, making regulation on the significant cost increase), it is unlikely that CCS demonstration projects can be deployed quickly and smoothly. Last but not the least, with the current available technology, deploying CCS in power plants will incur a cost increase at 60–80%, which will impose extraordinary high energy bill on the already fragile economy and is surely beyond the political and public acceptance. Therefore, if CCS is to be deployed in the U.S. at a meaningful scale, both federal and state politics will need to formulate initiatives to make CCS an economically, environmentally and politically viable technology.

Globally the U.S. is the strongest technology innovator and conventionally relies much on the market force to deploy technology innovation. However, considering the urgency and scale of climate change, it is unwise that U.S. should still afford the luxury of conventional, long-lead time for RD&D to bear results. New approaches must emphasize rapid commercialization of efficient, economic solutions that minimize CO_2 emissions. On February 2010, as required by President Obama, an Interagency Task Force on CCS was established to proposing a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 years [35]. As a response to the Obama's proposal, on December 2010, DOE updated the roadmap (Fig. 3) as the guidance for future CCS development [36]. According to the roadmap, first generation CCS technology should be ready for deployment at 2020 and advanced CCS technology should be ready for deployment at 2030. Though the roadmap is a manifestation of the determination of the Obama Administration, its timetable is still lagging behind the IEA roadmap and the factors discussed above are still there to hinder the rapid deployment of CCS in the U.S.

3.3. CCS in China

Though China is a late-comer in CCS sector, because of the great importance attached by the government, industry and research institute, encouraging progress has been made on policy formulation, technology R&D, pilot project implementation and international cooperation in China.

In February of 2006, the State Council of China issued the *Medium-and-long Term Science and Technology Development Plan 2006–2020 Year* [37]. High efficient, clean and zero CO_2 emission fossil energy technology is listed as the priority domain of advanced energy technology. In June of 2007, National Development and Reform Commission (NDRC) issued the *National Program on Climate Change* and CCS is highlighted in the program [38]. Soon in July of 2007, *the Special Program on Science and Technology in Response to Climate Change* was jointly issued by Ministry of Science and Technology (MOST), NDRC and other

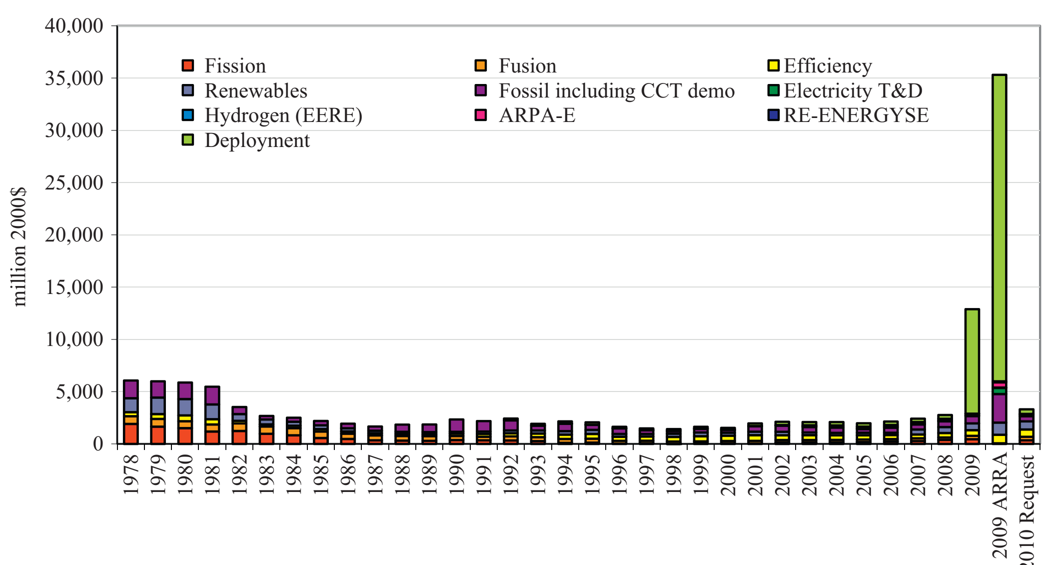

Fig. 2. Federal energy RD&D investments in U.S. between 1978 and 2010.
Source: [34].

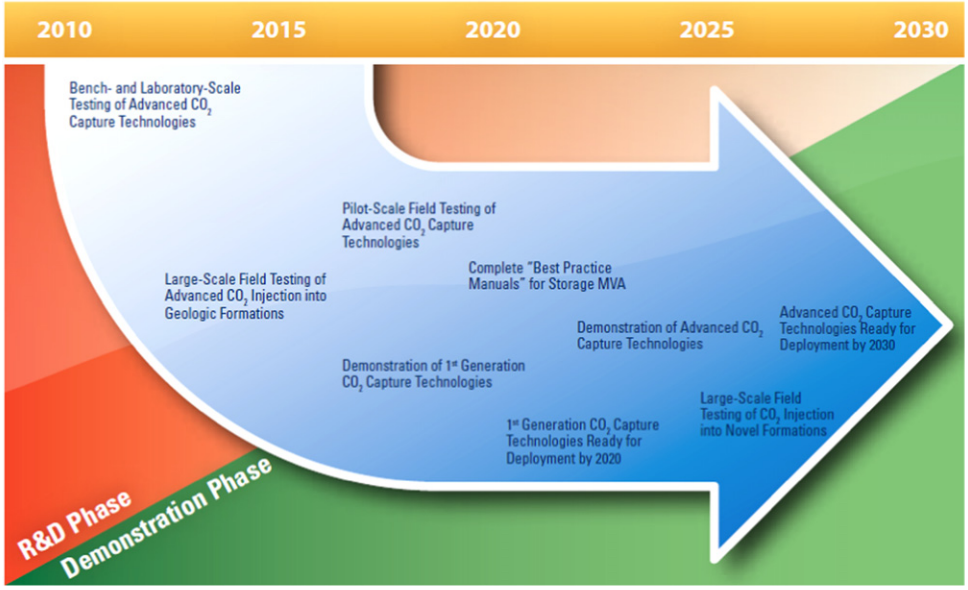

Fig. 3. The CCS roadmap of the U.S. by DOE/NETL.

ministries [39]. Carbon capture, utilization, and sequestration (CCUS) technology is listed among the key task priorities. Then in October of 2008, the Press Office of State Council (POSC) issued the white book of *Policy and Measures of Response to Climate Change in China*, which states clearly that "China has determined to advance research on CCUS as the key field in GHG reduction technology development" [40].

Currently, CCS is under research by the *National Major Science & Technology Project* managed by MOST. The 973 project "Improving the oil recovery rate by Greenhouse gases and their underground sequestration" was undertaken by Petro China, China Academy of Science, Perking University and other institutions. The project focuses on the key fields of CO_2 capture, transportation, application in EOR, sequestration and safety related issues. The 863 project "CO_2 capture and sequestration technology" was undertaken by Tsinghua University, China Academy of Science and China Huaneng Group. The project focuses on CO_2 capture technology of absorption and adsorption, and saline sequestration technology. By these projects, China's industry sector and research institute accumulate certain technological base and R&D capability.

Until the end of 2010, in China there are five CCS pilot projects in operation and another four projects under construction, mostly in power generation sector [41] (Table 6). It is worthwhile noting that Shenhua Ordos coal liquefaction project is the first whole process CCS saline aquifer sequestration project with prospective annual capacity of 3 million ton CO_2. Besides, though the 275 MW IGCC pilot project is cancelled in the U.S, in China a 265 MW IGCC project with annual CO_2 abatement capacity of 1.1 million ton is already under construction by China Huaneng Group in Tianjin and is expected to put in operation at 2011. Another 450 MW IGCC+CCS project is also under planning and is expected to build since 2014 and commission in 2016, with annual CO_2 captures capacity of 1.6 million tons for EOR. Totally, currently there are 12 IGCC power generation or polygeneration projects under planning or construction in China.

In China, networks are also evolving rapidly to support CCS research and pilot project development. According to a recent study by China Academy of Science, there are at least more than 40 universities or other institutes in China actively carrying out CCS research projects [43]. R&D efforts and planned pilot projects have arisen more recently but are growing quickly, with several projects already underway. Domestic initiatives and internationally linked projects have created CCS-focused networks connecting state-owned enterprises, government ministries, and international researchers and business. Most of the existing CCS projects have focused on carbon capture, from the 3000 t/year CO_2 capture project being carried out by the Huaneng Group and the Australian Commonwealth Scientific and Industrial Research Organization, to the IGCC-CCS projects like GreenGen. Domestic R&D networks for CCS are supported through several different initiatives and collaborations. Chinese state-owned industries have been involved in CCS-related activities actively: (1) PetroChina has spent roughly $29 million to study EOR activities since 2006; (2) Shenhua established the Beijing Research Institute of the Shenhua Coal to Liquid and Chemical Company; and (3) an industrial consortium has been formed to build the GreenGen IGCC project, with capture and storage of 1 million ton of CO_2 per year planned for Phase 2 after 2012. The GreenGen project links an international coalition headed by the largest state-owned power company in China, the Huaneng Group (the same company involved in the U.S.-based FutureGen), and includes China Datang Power Group, China Huadian Power Corporation, China Guodian Power Corporation, China Power Investment Corporation, Shenhua Group, State Development & Investment Co., China Coal Group, the Chinese government and the largest U.S.-based coal company, Peabody Energy. The ultimate aim of GreenGen project is high efficient coal-based power generation system with near-zero main pollutants and CO_2 emissions. As illustrated in Table 7, a three-stage roadmap has also been worked out for the GreenGen program.

International collaborations have been active in creating CCS networks in China. Bi- or multi-lateral networks have been created in collaborations with the U.S., the U.K., EU, Australia, Japan and the Asian Development Bank. Most projects support the development of advanced coal technologies and carbon capture technologies, and a few are analyzing the suitability of Chinese geological formations for storing CO_2. In 2003 China joined the Carbon Sequestration Leadership Forum (CSLF), a ministerial-level organization initiated by DOE. The initiative promotes collaborative research, deployment and demonstration of CCS projects among the CSLF signatory member countries. Among the seven recognized and completed CSLF projects, two are located in China. Of particular note is the Ordos Shenhua U.S.–China joint project, which aims to capture high purity CO_2 from a direct coal liquefaction facility and eventually sequester 2.9 million tons of

Table 6
List of pilot CCS projects (in operation and under construction) in China.
Source: [42].

Name of pilot project	CO_2 Captured	Construction time/progress	Operator	Location	Technology/CO_2 source	Investment (RMB ¥)
Beijing thermal power plant	3000 t/yr	Operation since July 2008	China HUANENG Group	Beijing	Chemical absorption without sequestration/flue gases of power plant	21 M
ShiDongKou No. 2 power plant	100,000 t/yr	Operation since December 2009	China HUANENG Group	Shanghai	Chemical absorption, no sequestration/ capture 4% flue gases from 2 × 660 MW supercritical units	150 M
Ordos coal liquefaction plant	Starting from 100,000 t/yr, upgraded to 1 M/yr and 3 M/yr in two steps	Operation since August 2010	China Shenhua Group	Ordos, Inner Mongolia	Compression + purification + sequestration by saline formations/direct coal liquefaction	210 M
Shuanghuai power plant	10,000 t/yr industry grade	Operation since January 2010	China Power Investment Corp.	Chongqing	Chemical absorption, no sequestration/ capture part of flue gases from 2 × 300 MW supercritical units	12.4 M
Wuhan Renewable Energy Institute oxy-combustion project	10,000 t/yr	2011	HUST	Wuhan	Oxy-combustion without sequestration	20 M
35 MW oxy-combustion project (phase I)	100,000 t/yr	2011–2014	HUST, Dongfang Electric	Yingcheng,Hubei province	Oxy-combustion without flue gases sequestration from 35 MW PV unit	85 M
35 MW oxy-combustion project (phase II)	100,000 t/yr	2015	HUST, Dongfang Electric	Yingcheng,Hubei province	Oxy-combustion without flue gases sequestration from 35 MW PV unit	–
Jinlin Oilfield CO_2-EOR pilot project	Injection of 300–400 t CO_2/day, planning of sequestration 1 Mt CO_2/yr from 2015	Pilot experiment from 2008	Petro China	Jinlin	Compression + purification + EOR/Natural gas field/	–
Binhai IGCC project	1 M ton CO_2/yr capture	Under construction since 2009 and expected to be in operation in 2011	China HUANENG Group	Tianjin	265 MW IGCC coal unit	2B

Table 7
Roadmap of GreenGen project in China.

Phase I: 2006–2011	• Construction of 250 MW pilot IGCC project • Development of 2000 t/day two-stage dry coal powder gasification boiler • Development of GreenGen laboratory
Phase II: 2011–2014	• Optimization of gasification boiler • Development of key technologies for Green coal generation • Preparation for pilot near-zero IGCC project
Phase III: 2014–2016	• Construction and operation of 400 MW IGCC-CCS project • Economic feasibility study and commercialization

CO_2. There are also two projects focused on creating preliminary guidelines for a legal and regulatory framework for CCS in China, the SRACO2 project is funded by the EU and the other, the Tsinghua-WRI partnership, is working with industry, academics and government to explore integrating CCS into Chinese regulatory frameworks. Additionally, the Asian Development Bank is funding the creation of a CCS Roadmap for China. Another important researcher, Huazhong University of Science and Technology (HUST), is carrying out oxy-combustion CCS technology R&D under U.S.–China cooperation, which will be discussed in the next section. HUST also works out a roadmap for oxy-combustion CCS technology in China, with the ultimate goal of developing 600 MW oxy-combustion units into commercialization application. According to the thermal economics analysis, oxy-combustion units have comparative economic advantages: the CO_2 CCS cost from the super-critical 600 MW and ultra super-critical 1000 MW unit is ¥157 (or $24.6 under current exchange rate) and ¥147 ($23), respectively, while capture-only cost is ¥114 ($17.8) and ¥108 ($16.9) [44]. According to the analysis, the price increase from super-critical 600 MW and ultra super-critical 1000 MW oxy-combustion capture-only unit range between ¥92 and ¥95/MWh, which is much lower than the current wind power price premium in China and is even more economically viable if coupled with EOR. The price increase from CCS unit ranges between ¥130 and ¥140/MWh, which is still lower than the current wind power price premium in China. However, utility-scale demonstration projects are needed to prove the theoretical analysis results.

Though China has been active on CCS technology R&DD and achieved quick progress, there are some important issues deserving attention. Firstly, CCS is not mentioned in the policy of the 11th five-year guidelines (covering 2006–2010) for reducing the GDP energy intensity by 20%. The energy penalty of CCS is often cited as a major barrier to deployment. The newly issued 12th five-year plan (2011–2015) on energy conservation and GHG reduction still does not integrate CCS as the one of the countermeasures. Many authors have questioned how the Chinese political context

translates into support for large-scale deployment of CCS. As [45] put it: "China's incentives for keeping on the forefront of CCS technology learning do not translate into incentives to massively deploy CCS in power plant applications as IEA scenarios would have it. In fact, fundamental and interrelated Chinese interests – in energy security, economic growth and development, and macroeconomic stability – directly argue against large-scale implementation of CCS in China unless such an implementation can be almost entirely supported by outside funding." Secondly, issues of economic viability (and who would pay for CCS) present a unique dilemma for the Chinese government. Passing on the increased costs of CCS to electricity customers would upset industries and the public and possibly affect economic growth, which is contrary to China's long-implemented strategy to maintain electricity price lower to boost economic growth. Requiring utilities to absorb the costs would erode not only their profit margin but also their support as a key stakeholder in deploying the technology. A third approach would be to fund (or co-fund) CCS deployment costs through outside party, through multilateral or bilateral cooperation. However, its feasibility depends on the trend of global climate policy. Thirdly, the regulatory framework for deploying CCS in China is almost in void, which will restrict its rapid deployment even if funding has been secured. And finally, the issues of public acceptance of CCS projects have become increasingly salient, with the number of public demonstrations against energy and waste facilities increasing rapidly.

3.4. Current U.S.–China CCS cooperation

In November 2009, President Barack Obama and President Hu Jintao announced the establishment of the Clean Energy Research Center (CERC). On November 17, 2009, U.S. Secretary of Energy Steven Chu, Chinese Minister of Science and Technology Wan Gang, and Chinese National Energy Administrator Zhang Guobao signed the U.S.–China CERC Protocol, launching the CERC. The primary purpose of the CERC is to facilitate joint research, development and commercialization of clean energy technologies between the U.S. and China. The program – funded by a bilateral $150 million in public–private funding – includes research groups, or "consortia," focused on building efficiency, electric vehicles and advanced coal technologies. The CERC will also build a foundation of knowledge, human capabilities and relationships in mutually beneficial areas that will emphasize clean energy in both nations. Within the three current CERC programs, the Clean Coal (including CCS) program addresses technology and practices for clean coal utilization and CCUS. The U.S. has chosen West Virginia University (WVU) and China has chosen Huazhong University of Science and Technology (HUST) to lead teams of experts from public and private institutions. These teams are designated as the China Advanced Coal Technology Consortium and the U.S. Advanced Coal Technology Consortium (the China ACTC and U.S. ACTC, respectively). These two Consortia will implement a five-year Joint Work Plan to significantly advance technology in the area of clean coal, including CCUS, in both countries.

The U.S. and Chinese governments have been cooperating on clean energy technologies for decades. In the past, collaboration on clean energy has taken place on a government-to-government, academic-to-academic, and business-to-business basis. On government level, the U.S. and China government have bilaterally cooperated on fossil energy RD&D since 2001, while on multilateral level both governments have cooperated through frameworks of CSLF, Asia Pacific Partnership on Clean Development and Climate (APP), APEC EGCFE Geosequestration Project, Global CCS Institute, etc. On academic and business level, there is wide extensive cooperation between the leading U.S. organizations as NETL, Pacific Northwest National Laboratory (PNNL), WVU, Duke Energy, etc. and leading China organizations as CAS, China Huaneng Group, China National Petroleum Corporation (CNPC), Shenhua Group, etc. (Table 8). However, the CERC program arguably represents a fundamentally new way of working together and firstly integrates activities into what both sides have said they wanted for a

Table 8
Joint U.S.–China CERC-ACTC research projects.

No.	China project name	China participants	U.S. project name	U.S. participants	Key features
1	Studies on near zero emission power-generation technology based on IGCC	NETC-CLCP, CHNG-CERI, CPECC, THU, CEP-CAS, CPIC, SJTU	IGCC with CCS at the million ton scale	Duke Energy, GE, LLNL, IGS, LANL, NETL, WVU: D. Mohler+R. Turtan	Operational study of IGCC of operation (best-practices)
			Pilot-scale IGCC research	UWY, GE, LANL: M. Northam+E. Norton	Gasification, gas clean-up, CO_2 separation w/many coal types+biomass
2	Large-scale post-combustion CO_2 capture, utilization and storage technology	NETC-CLCP, CHNG-CERI, CPECC, CPIC,THU	Advanced amine testing platform	Duke Energy, Alstom, WVU, NETL, UKy, B&W, LLNL: R. Smith+SJ Friedmann	Multiple facilities/pilots tests across the US capable of running a suite of tests; instrumentation at flagship facilities;
			Ammonia capture w/ integrated sequestration and scale-up	AEP, Alstom, Ramgen, UKy, NETL, LLNL, WVU: G. S pitznogel+K. Liu	Sequestration and scale-up of facility Integrated CCS today Chilled ammonia
3	The research on sequestration theory and simulation technology of CO_2 geological storage and large-scale storage strategy	Shenhua, IRSM-CAS THU, NWU, CUMT, Yanchang Petroleum	Sequestration capacity and near-term opportunities: Ordos Basin	UWY, WSGS, WVU, LANL, LLNL, NETL: R. Surdam+T.Carr	Site characterization; modeling; risk assessment; brine treatment
			Conventional EOR opportunities and practice	WSGS, UWY, WVU, LLNL: D. Mohrbacher	Reservoir characterization and ranking, monitoring planning and design
4	Microalgae bio-sequestration of CO_2 from flue gas of power plant	ENN, ZJU, CEP-CAS	CO_2–algae bio-fixation and use	Duke Energy, UKy, NETL: R. Smith	Bio-reactor or pond-based algae capture and re-use
5	Theory and equipment development for oxy-fuel combustion	HUST, THU, CPECC, HIT	Theory, development and demonstration of oxyfiring combustion	B&W, Alstom, WVU, LLNL, NETL: K. McCauley+SJ. Friedmann	Oxy-combustion repowering(200 MW) with deep saline fm. storage; novel CO_2 compressors; multiple US facilities for fundamental pilot and coal combustion tests
6	Combined coal pyrolysis, gasification and combustion multi-generation technology	ZJU, CEP-CAS CUMT	Coal-to-Chemicals, with capture & co-gen	LP Amina, WVU, LLNL: W. latta+I. Celik	Pyrolysis, gasification and oxy-chemical combustion for power and chemical production

long time—a genuine public–private partnership. This program has thus laid a firm foundation for deeper and wider U.S.–China energy cooperation in the future.

4. Why stronger U.S.–China collaboration is possible?

4.1. Common GHG reduction and energy security concerns

Together, China and the U.S. hold over 43% of proven global coal reserves, with the U.S. possessing an estimated 238 billion tons of coal and China having estimated reserves of 114 billion tons [46]. Most coal in the U.S. is used to produce electricity, with roughly half of all electricity generated by coal-fired power plants, and the growth in electricity demand remains relatively flat. China is growing rapidly and is currently the world's largest coal producer and consumer. China uses 46% of the hard coal produced worldwide, and the Chinese electricity sector consumes 58% of this coal, with demand expanding at rates of 13–14% annually [3]. Within the Chinese electric sector, 79% of electricity is produced by coal-fired power plants. The IEA projects that over the next 20–30 years, an additional 1000 GW of coal capacity will be built in China, and coal will continue to supply more than 70% of total power generation [3]. This increase in coal occurs in spite of the Chinese Government's aggressive policies to create a low-carbon power system, including the enacted energy efficiency goals and the planned rapid addition of nuclear and wind power. Analyses of scenarios of energy saving and low-carbon development in China by NDRC Energy Research Institute project that coal use in 2050 will have more than doubled under the baseline scenario, or increased by 1.5 times under a low-carbon scenario, with associated CO_2 emissions estimated at 12.8–8.5 billion tons of CO_2 per year [47].

From a climate policy perspective, the U.S. has failed to provide leadership on climate change, which is inappropriate with its super power status. To preserve its leading position, the U.S. will ultimately assume its responsibility on climate change. As the largest emitter of CO_2 in the world and with emissions projected to double over the next 50 years, China is under increasing international pressure to reduce its GHG emissions (refer to Fig. 4 for an overview of CO_2 emissions in China and the U.S, Figs. 5–9 for structural analysis of energy consumption, energy supply, CO_2 emissions and power generation in China and the U.S). Cooperation on climate policy will definitely enhance the soft power and improve the external environment for the rise of China. Therefore, on the assumption that both countries will act responsibly, cooperation on global climate policy formulation between U.S. and China will not only help

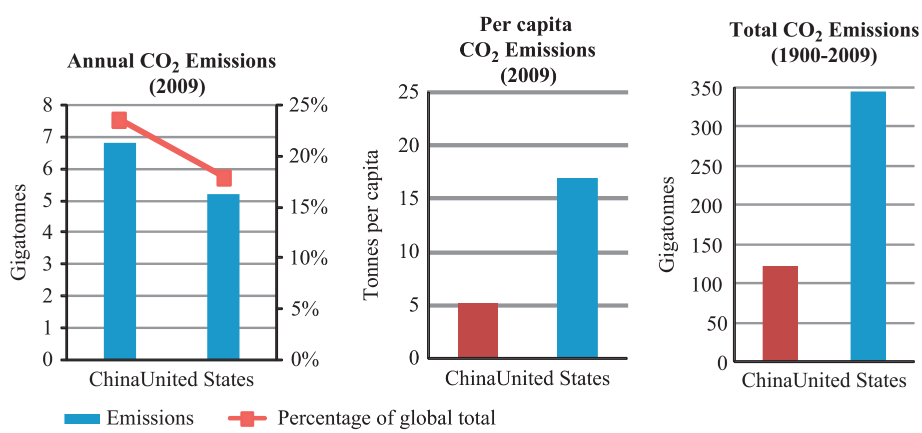

Fig. 4. Comparison of annual, per capita and total CO_2 emissions in China and the U.S.
Source: [48] for 2008, 2009 data and the Carbon Dioxide Information Analysis Center (CDIAC) for 1900–2007 data (http://cdiac.ornl.gov/).

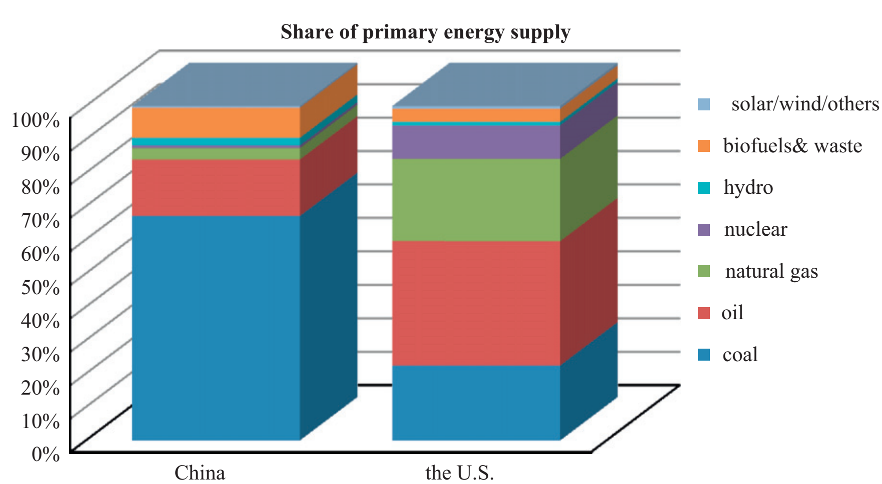

Fig. 5. Comparison of energy supply structure in China and the U.S. at 2009.
Source: [49].

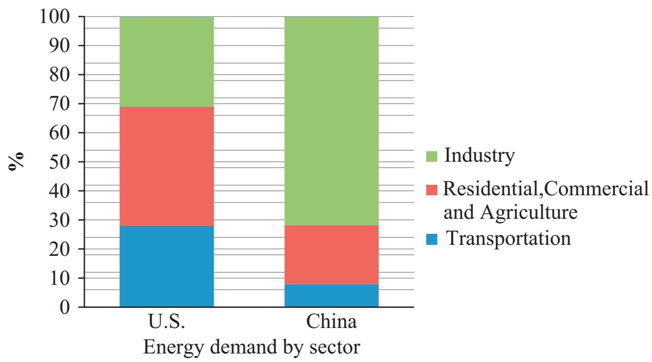

Fig. 6. Comparison of energy demand by sector in China and the U.S. at 2009. *Source*: [49].

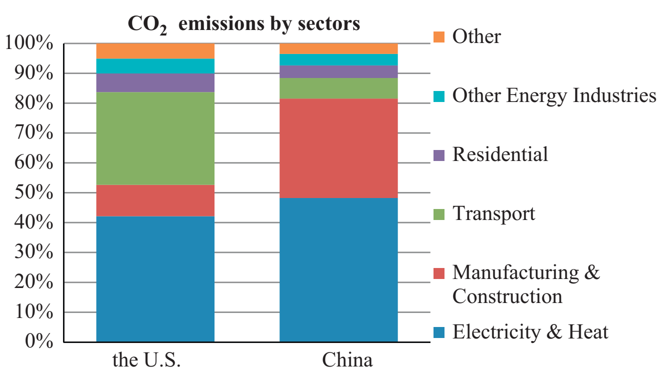

Fig. 7. Comparison of CO_2 emissions by sector in China and the U.S. at 2009. *Source*: [49].

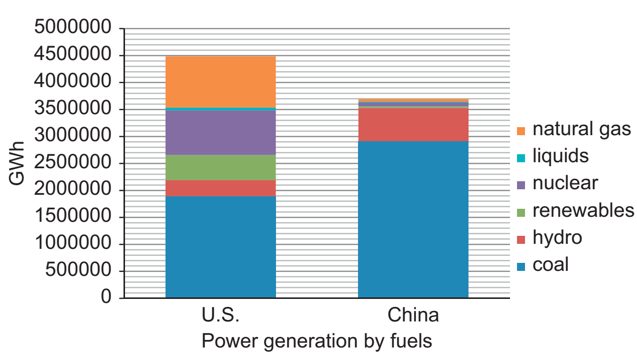

Fig. 8. Comparison of power generation mix in China and the U.S. at 2009. *Source*: [49].

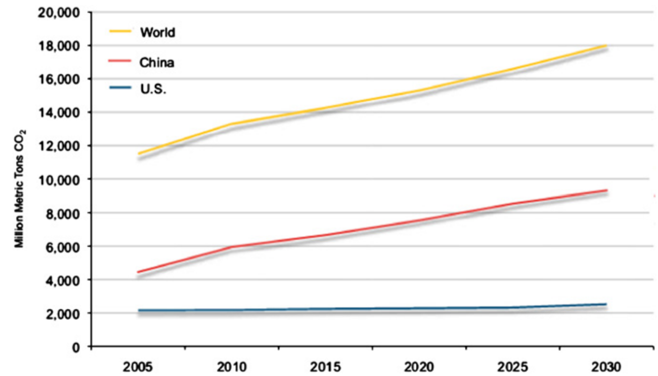

Fig. 9. Comparison of CO_2 emissions from coal use and projection in China and the U.S.
Source: [50]. Note: 2005 data is actual; 2010–2030 data is projected.

ensure energy supply for both countries, but also encourage energy technology development, transfer and deploy, create business opportunities and contribute to global environment protection.

CCS could allow both China and the U.S. to continue to use their extensive coal reserves and take advantage of existing infrastructure in a carbon-managed world. Both China and the U.S. also have many potential places to deploy CCS technology and many different opportunities for low-cost capture. As China is rich in coal resources (13.9% of the world's proven reserves) but relatively poor in oil and natural gas reserves [46], there is strong economic and energy security pressure to use coal in the industrial sector, including producing iron, steel, ammonia, and coke and for petroleum refining, and in new coal-to-liquid projects. There are an estimated 400 operating and planned industrial facilities in China, which when fully operational, will emit 270 million tons per year of relatively pure CO_2, creating many low-cost opportunities for capture [42]. The U.S. also has potential low-cost sources for CO_2 capture from industrial facilities, including ethanol plants and refineries [51]. Both countries also appear to have promising geological targets for storing captured CO_2, from initial EOR opportunities to saline aquifers [52]. While the storage capacity of China has not been studied as that of the U.S., several promising areas for further exploration have been identified and could provide vast possibility for near-term deployment [42,53].

In the U.S., 80% of domestic oil consumption comes from import, mostly from Middle East nations conflicted with consistent conflicts or terrorism. Energy security is closely related to foreign relation and military policy, which are often subject to criticize for long time. In China, according to IEA projection, with the growing energy demand, oil import dependence will increase from nearly 50% today to 80% in 2030 [54]. Coal will continue to dominate China's energy mix for decades to come. Coal accounts for about 94% of China's proved fossil fuel reserves and about 70% of China's total energy consumption, thereby providing stability in China's economic growth so long as coal reserves last [55]. Coal consumption is expected to grow most rapidly in the near term, boosting coal's share of total primary energy demand by three percentage points to a peak of 66% around 2010, before falling back to 63% by 2030. Coal is by far the leading contributor to China's CO_2 emissions and remains so in the IEA's Reference Scenario through 2030. Coal's share of emissions falls only slightly after 2030, from 82% to 78% [54].

4.2. Common though differentiated economic and development challenges

Economic considerations shape the perceptions of CCS differently in the U.S. and China. China's development goals of "moderate prosperity" include bringing the per-capita income level to $10,000[56]. However, the rapidly increasing energy consumption, especially that of coal has resulted in serious environment degeneration and puzzle of sustainable development. On the other hand, China is facing increasing international pressure to reduce emissions and commit to long-term reductions under the post-Kyoto framework. To turn challenges into opportunities, China takes clean energy as one of new strategic industries to promote the long-term structure adjustment.

In the U.S., economic worries and slow economic growth focus attention on cutting costs, shrinking government budgets, promoting private investment and creating jobs. The Obama Administration has taken clean energy as the engine for economy

revitalizing. It is reported that the implementation of the ACES Act would unleash private sector investment in clean energy to create millions of new jobs that cannot be shipped overseas and make America the global innovation leader on clean energy technology. It is therefore important that if U.S.–China could make any significant cooperation on energy, it is necessary that the cooperation should directly promote American employment. We would thus argue that deeper and wider U.S.–China collaboration on CCS can promote two nations' strategic economic development.

4.3. Complementary political, economic and market factors

The socio-political context for deploying CCS in China and the U.S. is totally different. Two countries have different political and economic system, as well as different energy industry structure. According to [57] these differences would potentially make large-scale CCS deployment challenging. On the other hand, there are significant differences on the NIS and energy strategy in both countries (Table 9). In our opinion, it is rightly the existence of these seemly different but complementary factors, coupled with the factors discussed above, that will effectively make stronger U.S.–China CCS cooperation possible and feasible.

First of all, though the U.S. is leading in CCS technology R&D and field test at pilot scale, the verification of the commercial feasibility of the technology needs the strict field test of large-scale demonstration projects, preferably incorporating different integration designs and adapting to different fuel sources, which, in turn requires related legislation at national level and cooperation at state level. However, the failure to pass ACES in the congress and no new legislation imitative after that clearly indicates that the gridlock in the U.S. political system would virtually block the near-term LSIP demonstration of CCS. On the other side, with the centralized political and decision-making system in China, coupled with the Government's emphasis on clean development and industry's enthusiasm on clean technology, it is highly possible for quick demonstration of LSIPs in China in the near term. However, besides cost issue, the biggest worry of China for demonstrating large-scale CCS projects concerns with the technology feasibility and security issues, which is rightly the advantages of the U.S. Secondly, currently the U.S. economy is attacked by financial crisis, resulting in poor growth and persistent high unemployment rate. The gloomy economic perspective would render the reverse of historical declining trend of energy R&D funding difficult, not to speak of the tremendous fund requirement for LSIPs. On the contrary, investment on clean energy in China, from both public and private sector, is currently gaining its momentum and is expected to take the leadership in the future globally. The plenteous fund input would render the rapid demonstration of LSIPs possible in China, particular if with the technology and fund support from the U.S. Thirdly, considering the future power demand, retrofitting of existing power plant would be a priority for CCS deployment in the U.S. However, because of the complex ownership and regulation structures, as well as the decreasing public attention towards climate change and the customer worry on bill increase, even with proper legislation and funding support, demonstration of CCS in utility would definitely be a time-consuming and troublesome process in the U.S. But because the power sector is largely state-owned in China, the same problem is absolutely not so serious in China.

Last but not the least important, a closer cooperation will definitely facilitate the implementation of energy strategy in both countries. If China and the U.S. could further closer cooperation on CCS, the U.S. could benefit much in advancing the CCS technology, and more importantly, developing the global CCS market. A close cooperation would thus facilitate one of the energy strategy considerations of the Obama Administration, namely leading the world towards safer and more secure energy supplies. U.S. has already lost its leadership on clean energy development, while a closer cooperation on CCS would help the U.S. regain its position. On the other hand, the cooperation will help China advance towards clean coal strategy.

5. The possible U.S.–China CCS cooperation model and the benefits

5.1. Key considerations and principles of the cooperation

5.1.1. Considerations on suitable role and responsibility of two countries

In November 2009, just before UNFCCC Copenhagen conference (COP15), a report jointly worked out by Asian Society and Center for American Progress issued a roadmap for U.S.–China cooperation on CCS, which is a detailed unfold of the wider U.S.–China cooperation on energy and climate change (an Initiative for U.S.–China Cooperation on Energy and Climate, which is chaired by Steven Chou, the subsequent Secretary of Ministry of Energy in Obama Administration) [63,64]. The report has proposed a three-prong program (Table 10) outlining a process that can produce early milestones while working toward the longer-term goals, which exerts significant impact on the current U.S.–China CERC cooperation mechanism.

The roadmap helps address many of the concerns and hurdles that have impeded the use of CCS as a meaningful solution to the climate change challenge. Firstly, the relatively low-cost early actions should allow both countries to start demonstrating new leadership in the near term. Secondly, accelerating the development of CCS practices, protocols, and standards should help provide businesses and governments the information they need to invest in and deploy CCS more confidently and swiftly in the future. Successful deployment can also help to keep energy costs low and accelerate the development of green-collar CCS jobs in key U.S. and Chinese regions and markets. Thirdly, the roadmap could lead to the creation of financial mechanisms to support large-scale projects at relatively low cost. Finally, the roadmap could accelerate cost reduction and provide field experience needed to scale up the mass deployment of CCS rapidly enough to make a meaningful impact on emissions worldwide [64].

The report proposes that in the near term (0–5 years), five sequestration projects (sequestrating 10–15 million tons of CO_2 each year) in China's gasifier industry could be co-sponsored by China and the U.S. on 60% and 40% share, respectively. The public funds from the U.S. side will be used to support U.S. companies to participate in sequestration projects in China. The roadmap also proposes that 1500 MW CCS projects in China's power sector (sequestrating 9 million tons of CO_2 each year) could be deployed sponsored by China but backed up by the U.S. with a CESA style guaranteed payment. However, because of the failure of passing CESA in the U.S., such guarantee would be virtually meaningless and could not provide confidence to China Government and industry stakeholders in both countries.

Though the report admits that the cooperation must not only be built on mutual respect and recognition of both countries′ expertise and incentives, it doesn't take the perspectives of related stakeholders into careful consideration. First of all, it overestimates the Obama Administration's capability on clean energy and climate change legislation and the basic assumption of the report is that CESA or similar act will soon be passed and put into effect in the U.S. Secondly, in the report the seemly equal position actually tilts towards the U.S. in that China is mainly regarded as a test field for the (unproved) technology developed by American companies or

Table 9
The socio-political context for deploying CCS in China and the U.S.

Political process and government structure	
China: Single-party system, the Politburo of the Party makes major decisions and then extends into policy platform by CPC, the policy is then turned into national policy or legislation by NPC. The State Council and its ministries can execute with their ordinances and regulations without enactment of law and retain kinds of means (including appropriation) to execute	The U.S.: Separation of the executive, legislative and judicial powers; federalism; two-party system; complex House/Senate-President legislation procedure; the expense of federal government and its ministries subject to the parliament appropriation. Under federal system, individual state retain rights to economic affairs under its jurisdiction
Economic system	
China: Planned market economy with lot of government intervention	The U.S.: *Laissez faire* market economy with minimized government intervention
National innovation system (NIS)	
China: Weak but enhancing basic R&D capability. Low contribution of innovation to long-term economic growth and concentration of low value-added industry. Weak indigenous technology development capability and dependence on external source of technology. Weak Capabilities to Absorb and Adapt Imported Technologies. Government-dominated innovation system but lack of clear technology deployment policy. Lack of Integration between government industry and university. Poor protection of Intellectual Property Rights	The U.S.: Best basic R&D capability; best research universities, national laboratories and scientists. Innovation is essential for long-term economic growth national competitiveness. Private sector is the innovation engine and government is innovation facilitator. Market-based innovation with strong government-university-industry public-private partnership. Strong protection of Intellectual Property Rights
Energy strategy	
China: Stable, economical, clean and sustainable energy system; energy conservation as a long-term priority; scientific development, and clean and high efficient utilization of coal; stabilizing oil supply and enhancing domestic gas production; vigorously developing hydropower and renewable energy; actively developing nuclear power with safety in consideration [55]	The U.S.: 21st century clean energy economy; developing and securing America's Energy supplies; providing consumers With choices to reduce costs and save Energy; innovating to a clean energy future [56]
Energy industry and CCS stakeholders	
Coal companies: China and the U.S. are the world's two largest coal markets. Coal companies in the U.S. are private companies, whereas in China, the industry is dominated by state-owned enterprises	
China: Large, fragmented market. While over 27 provinces produce coal, major production is dominated by Shanxi Province and Inner Mongolia. The industry is undergoing restructuring and is currently dominated by many large and powerful state-owned enterprises. The largest coal company in the world, Shenhua, controls 9% of the market. Additionally, international coal companies, like Peabody, are involved in the Green-Gen demonstration project in China	*U.S.:* Large market, with production concentrated in the west (Wyoming and Montana) and east in Appalachia. Western producers (Peabody, RioTinto, Arch) and eastern producers (CONSOL, Alliance, Foundation and Murray) are some of the largest firms involved in coal production, and 90% of produced coal is used in the electric power sector. The Coal Utilization Research Council is the industry lobbying organization
Power Companies. Electric power generation in both countries is dependent on coal use. Rapidly increasing electricity demand in China has led to challenges in providing sufficient power while in the U.S. electricity demand is flat in the future	
China: There are five large state-owned companies (Huaneng, Datang, Huadian, Guodian, and Zhongdiantou) with 50% of the market. The electric sector contributes 40% of national CO_2 emissions. Electricity prices are set by the central government by the NDRC (see below), and vary slightly by type (e.g., industrial or residential) and location	*U.S.:* The four largest power companies in terms of both generation and coal use in the U.S. are American Electric Power, Southern Company, Duke Power and the Tennessee Valley Authority. Over 63% of all power sold in the U.S. is by investor-owned utilities, while ~25% is from consumer-owned utilities. Each type has a different institutional structure, as well as a slightly different regulatory and financial environment. In general, all state electric utilities are regulated by the state Public Utility Commissions under a very heterogeneous regulatory environment
Oil and Gas Industries: Both countries are large petroleum importers, and oil supplies are an important geopolitical energy security issue	
China: China has limited oil and natural gas supplies, but rapidly increasing demand. Chinese oil companies are active domestically, exploiting older oil fields in the east and new fields in western China, as well as globally. They include the China National Petroleum Corporation (CNPC), the China National Offshore Oil Corp, and Sinopec	*U.S.:* The U.S. has significant oil and gas reserves, but even larger demand. Production is dominated by private industry, though the major global oil companies are only active in Alaska. While oil production occurs in over 39 states, it is the dominant industry in only a few western states
Industrial facilities: Capture of CO_2 from industrial facilities could be significantly cheaper than from coal-fired power plants. Additionally, many such facilities in China also use coal, whereas in the U.S., this is much less prevalent. In both nations, industrial facilities could provide significant opportunities for early capture	
China: A combination of state-owned enterprises in ammonia, cement, iron and steel production and refineries managed by different government agencies. Potentially, 270 million tons of CO_2 are available for low-cost capture from existing and planned industrial operations. Most are concentrated in eastern China	*US:* Privately owned, could provide interesting early capture opportunities. Examples are refineries, chemical facilities, cement manufacturing, and upstream oil and gas operations [48]. They are concentrated in the east, midwest, and along the west coast. For example, bio-ethanol plants owned by ADM are involved in a CCS capture demonstration project
Environmental Non-Profit: While environmental non-profits play an important role in U.S. politics, there is no similar role in China. Both Chinese and international NGOs have been established in China	
China: Local and international groups exist, but given China's governing system, they currently play a very limited role in central policy making. However, many popular protests spurred by local environmental pollution have been documented [57]	*U.S.:* World Resources Institute, Environmental Defense Fund, Natural Resources Defense Council, Sierra Club, Pew Center on Global Climate Change, Union of Concerned Scientists, Greenpeace, and others, are actively involved in policy and advocacy, with some being for and some against CCS and acting in very different roles
Relevant Government Actors on energy and climate issues: the Chinese and U.S. governing systems are dramatically different, and the roles played by the central/federal government and the provinces/states reflect this. One similarity is that environmental or energy policies made at the national level are often implemented, at least partially, by state or provincial actors. However, the actors involved, their relative power and influence and political pathways and priorities are all very different [58]	
China: National Development and Reform Commission (NDRC) sets wholesale and retail electricity prices. The Department of Climate Change is located in this ministry. The NDRC currently has the ultimate authority for approving large power sector and industrial projects, integrating consultation and approval from other ministries. National Energy Administration: sets policy and approves projects; formerly part of the NDRC and currently continues to have a strong relationship with the NDRC. Ministry of Science and Technology (MOST): in charge of scientific research agenda and funding. Ministry of Land and Resources (MLR): in charge of general land use, interacting with local governments and NDRC; purview over mineral rights and Chinese geological information. Ministry	*U.S.:* Department of Energy: funds CCS-related research through CCS Regional Partnerships, grants, loans and other activity. The Office of Fossil Energy's National Energy Technology Laboratory is involved in funding and the research agenda. Other National Laboratories (Livermore, Sandia, Berkeley, Los Alamos) also very involved in CCS-related projects. Environmental Protection Agency: charged with enforcing the Clean Air Act and Safe Drinking Water Act, which includes the Underground Injection Control Program, supporting research into regulations for environmental health and safety issues associated with CCS. Department of the Interior: in charge of public lands, especially important in the western U.S. The Bureau of Land Management (onshore) and Minerals Management Service

Table 9 (*continued*)

of Environmental Protection (MEP): oversees environmental protection and environmental impact assessments. The decision process between the MEP, the MLR and the MDRC is unclear. Ministry of Water Resources (MWR): charged with protecting ground and surface waters, as well as the planning, construction, and management of water-related infrastructure, including dams, water distribution and hydro-power stations. Provincial Governments: in charge of local project approvals and property and water allocations. Many of the central government structures are replicated at the provincial level	(offshore) are of particular interest. U.S. Treasury: finance and Internal Revenue Service which could influence tax code, rates, and reporting associated with CCS projects. U.S. Geological Survey: underfunded and understaffed agency with information on subsurface resources. State Level Agencies: property rights, electric power, and enforcement of most environmental actions happen as the state level. Key organizations are: Public Utilities Commissions, Departments of Oil and Gas, Departments of the Environment, State Geologic Surveys

Note: revised from [57] based on [58–62].

Table 10
The three-prong U.S.–China roadmap for cooperation on CCS proposed by Asia Society.

1. Sequestration of available pure streams of CO_2
- Rapidly implement demonstrations of geological carbon sequestration for existing low cost, pure streams of CO_2 in China

2. Retrofit research, development, and deployment
- Spearhead a major new collaborative research and development project on both the capture and the sequestration aspects of CO_2 produced by conventional coal-fired plants in both the United States and China
- Identify potential large-scale pulverized coal combustion projects that are ready for retrofits in China and the United States
- Outline a strategy to begin retrofitting plants in both countries, while at the same time continuing to find comprehensive ways to lower costs, improve effectiveness and advance scale-up

3. Catalyze markets for CCS
- Establish mechanisms to guarantee that companies that store carbon now will be paid a certain amount per ton at a point in the future, either by the private market for carbon or by the government in the event that market has not developed sufficiently

institutions while the risk of failure is mainly assumed by China. Thirdly, the report assumes that U.S. will be in a position of CCS technology provider and China will be in a position of technology recipient. It neglects the fact that there is no commercially feasible integrated CCS technology in the U.S.; and without the earlier demonstration projects (envisioned in the report) mainly funded by China, it is unlike that the technology could be proven or improved. It also neglects the fact that China has already made significant progress on some CCS technologies as IGCC or carbon sequestration in direct coal liquefaction project.

5.1.2. *Consideration from the perspective of innovation process*

Deploying CCS in large scale is a systematic innovation process. Therefore, a clear understanding of the innovation process is important for designing the U.S.–China cooperation model. According to the standard pipeline model in innovation theory, the major obstacle to innovation, namely the "valley of death", is the gap in support and financing between basic research and later-stage development. As a result, the success of many major innovations has typically depended on a strong injection of public money enabling them to bridge this valley of death [65]. On the reverse side, according to market-pull model, the innovators make these long-term investments on new technologies in R&DD only when they are convinced that the new environment is admirable. While these two theories address on the process by which innovation occurs and the external influences to which it responds, the third theory, innovation organization addresses the management of innovation and the organizations in which it takes place. Organization mechanisms is needed to help bridge the gaps between public and private sectors and institutions are needed to help smooth the interaction between public, private and academic sectors.

Unfortunately, clean energy technology innovation poses multiple challenges to the innovation models in that solution to energy transition is a vast and complex array on both the supply and demand sides while the powerful entrenched array of incumbent is resistant to change. CCS is a very special case. Unlike other clean energy technology as wind or solar power it does not provide new economic value to the customers but only provides global public goods under provider's net cost. Therefore, neither "supply-push" nor "market-pull" model can effectively work for it. The innovation of CCS technology can only be facilitated by organized efforts thus innovation organization is the key to its deployment. Further, because GHG emissions are of global effect, CCS provides global public goods and the organization on its deployment must be designed in a global perspective.

Since the Copenhagen Accord has not led to a global target for GHG emissions and gives little guidance to the private sector to deploy clean energy technology, bottom-up and technology-specific policies are gaining importance. A 2010 report [66] addressed the issue of strengthening clean energy cooperation under the UNFCCC framework. In this report, a framework is proposed to integrate the current three core elements of international technology cooperation, including technology networks and roadmaps, multilateral/bilateral R&D cooperation and technology demonstration partnerships (Fig. 10).

This report highlights the cooperation programs will be most effective if they: (1) focus on well defined and broadly endorsed national priorities; (2) strengthen developing country capacity and enabling environments; (3) apply a comprehensive approach at sufficient scale over multiple years; (4) build long-term public and private partnerships; (5) engage countries from all regions and promote broad knowledge sharing; and (6) coordinate and harmonize international support. We believe that these general principles are perfectly applicable to CCS technology.

5.2. *The possible cooperation model*

When discussing a stronger U.S.–China CCS cooperation, we mean not merely cooperation on technology development level, but a comprehensive model incorporating shared vision on global CCS deployment, coordination of national CCS policy, interrelated and coordinated CCS R&DD roadmap planning, determined public fund support on CCS R&DDD with strong private partnership, joint

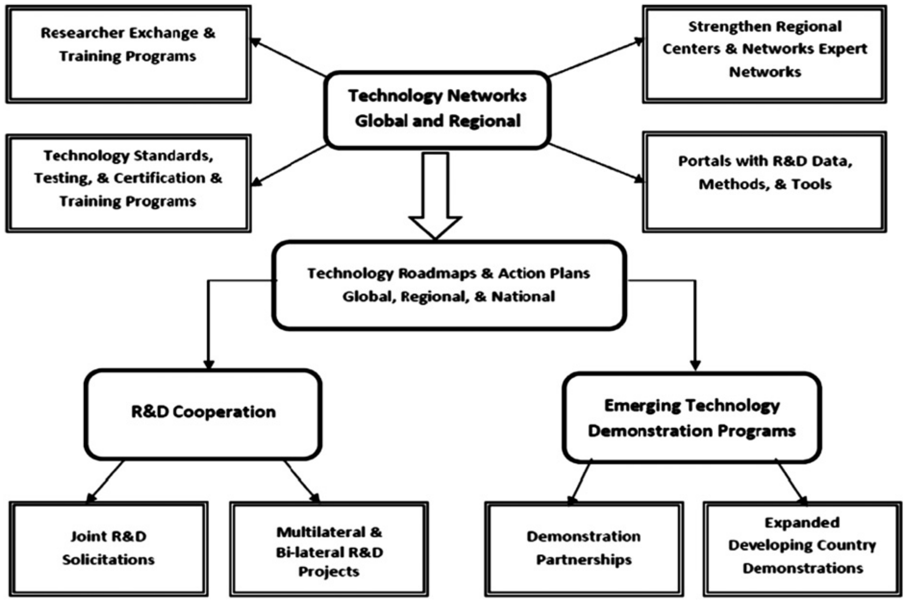

Fig. 10. The integrated model for international clean energy technology cooperation propose by NREL.

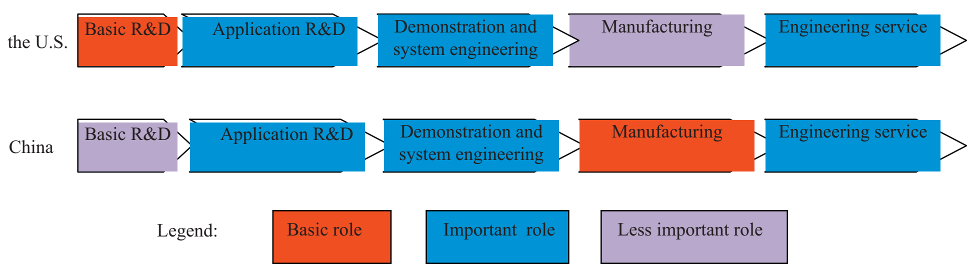

Fig. 11. The allocation of roles of the U.S. and China on CCS cooperation.

efforts on rapid global CCS deployment (including quick experience accumulation, standardization of technology, equipment and procedure and low-cost manufacturing) and most importantly, joint policy efforts to shape the global policy framework on CCS deployment. Because the full details of the cooperation are too complex and thus beyond the scope of the paper, we are only discussing the main aspects of the model.

First of all, the current cooperation between the two nations needs to be expanded to a comprehensive pattern with the rapid global CCS deployment as the ultimate target. The main roles of both nations in the cooperation should be carefully designed. According to the discussion above, in the whole process of CCS commercial deployment, the basic role of the U.S. could be focused on basic R&D of the technology, while that of China could be focused on low-cost manufacturing of the technology. But it does not exclude the U.S. companies from the manufacturing the key components of the system, neither does it exclude the involvement of competent China University or companies from the basic R&D activity by participating or investing in the joint R&D program. Besides, the important roles of the U.S. and China include the application R&D, demonstration and system engineering of the technology, as well as engineering service for the projects, according to the coordinated R&DD responsibility by the shared vision and the implementation planning. The implication is the maximum R&D progress, field experience accumulation and system integration for the proved technology in limited time by careful allocation of R&DD fund in different aspects and stages of the technology, and different research networks from two nations (Fig. 11).

Secondly, the organization framework must be carefully managed. Based on the study of [63], the current CERC-ACTC cooperation mechanism could be expanded in the following directions:

- A high level steering committee, chaired for the United States by the Secretary of DOE and for China by the Minister of MOST and the Administrator of NEA, consisted of representatives from interested ministries, departments and agencies of each country shall be set up. The main duty of the committee is to determine the vision of the cooperation between the two countries, determine the principles and framework of cooperation, approve and monitor the roadmap and the joint implementation planning as mutually agreed, endorse and monitor the support fund and its budget, and provide high level review and guidance for the activities and the direction of the program. The steering committee is also responsible for policy coordination and information exchange with related international agency as IEA, UNFCCCC, Major Economies Forum on Energy and Climate Change, etc.
- A Joint High Level Advisory Panel (hereinafter the Advisory Panel) consisted of business and academic experts selected by the Joint Steering Committee from each country shall be formed and supply the steering committee with suggestions and insights to ensure that issues of importance to the business and academic sectors on the state of, and needs for CCS deployment are brought to the attention of the Joint Steering Committee. The Advisory Panel should meet annually and update its experts along with the changes in the priority areas, and shall be responsible for reaching out to the U.S. and

Chinese CCS communities for their suggestions and to encourage their participation in the cooperation activities.

- Research networks (as the FutureGen in the U.S. and the GreenGen in China) consisted of related academic institutions, industry companies as well as NGOs will assume the specific duty of CCS R&DD approved by the steering committee on a combination of designation (like the current CERC mechanism) and tournament to ensure the speed and efficiency required by rapid deployment of the technology. It is important that industry players like power generator, utility, energy company, technology (and equipment) company, etc. are properly organized into the research networks to contribute to the basic and application R&D, project demonstration, system integration and ultimately mature technology supply, with their interests into proper consideration. The project results from the implementation by member of the networks of the both sides shall be disseminated and accessed according to the policy formulated by the steering committee to ensure effective information sharing, proper property right protection and free provision of best practices and procedures to other countries. The involvement of NGOs in the network has three-fold functions. First of all, NGOs like World Resource Institute and Pew Center, etc. can serve as valuable intelligent resource and directly participate in the R&D and policy counseling process. Secondly, NGOs can monitor the process and progress of the projects, especially the aspects closely linking with regional ecological or healthy issues. Thirdly, NGOs can serve as important channel on public communication and information dissemination. By close observation and monitoring of the projects, the NGOs are in an advantageous position to communicate with the public on the technological, economical and environmental viability of CCS.

Thirdly, the mechanism of the funding shall be designed and the scale of the funding be expanded. To fill the gap on CCS R&DD, the U.S. and China shall contribute between 5 and 10 billion USD$, from both public and private sector. According to [20], clean energy funding approaches need to be tailored to the different stages of technology development. Government funding is most relevant for early stage technology development, while private finance tends to assume a larger share of later-stage technology deployment and commercialization. CCS requires significant investment in large-scale demonstration and related infrastructure, and the critical period before commercial scaling carries high financial risks and requires sufficient regulatory frameworks. Private sector funders, regardless of institution class, unanimously point to consistent, well-articulated and long-term public policy as the most important criterion when considering investment in the clean energy arena. Therefore targeted public funding designed to leverage private sector finance can help to offset the greatest risks for CCS technology. We thus suggest that the governments of U.S. and China respectively provide one billion USD$ public money on CCS R&DD to catalyze private funding. A significant of the public funding can be provided by competitive tendering to ensure the benefits are directed toward the most efficiently run projects. With such significant amount of public funding from two nations, and the specially tailored national policy as tax exemption, subsidization of capital cost, and low-interest loans/loan guarantees, etc. [20,22], some 5–10 times of private fund is expected to be invested in CCS in both nations, which will significantly enhance the funding support and speed up the global CCS deployment.

An important note is that the model proposed in the paper is intended to complement, but not substitute, other ongoing bilateral and multilateral collaborations on CCS that China or the U.S. has with other countries. By working in parallel, the hope is that the collective efforts will lead and yield lessons that help accelerate CCS deployment globally.

5.3. Milestones and priority area of the cooperation

In this section, we will discuss the milestones and priority areas in both countries to materialize the cooperation. In line with the IEA roadmap, we will discuss the milestones in three phases of 2011–2015, 2016–2020 and 2020–2030. According to IEA analysis, 2030 marks an important time that CCS should enter into its large-scale commercialization stage. The key milestones in our analysis are based upon the requirement of the IEA roadmap and then translate them into the requirements on U.S.–China cooperation (Table 11).

According to the milestone envisioned in the paper, during the 2011–2015 period, the main focus of the cooperation is on the commercial feasibility of some CCS technologies with solid laboratory and field test base by demonstration of LSIPs. Reaching agreement on long-term vision of CCS deployment and concrete cooperation plan and mechanism are key points for future success. To minimize the possible public opposition and the political risks of CCS deployment in the U.S., the cooperation can start with 2–3 LSIPs in China. With the experience accumulated in China, demonstrations of utility-level projects can then be implemented in the U.S. To speed up the large-scale deployment in China, at this stage China needs to work out the national geological storage map and the transportation pipeline network configuration with the help from the U.S. Meanwhile, the regulation framework for CCS is also important for later stage deployment. During the 2016–2020 period, the focus of the cooperation is the commercialization of the proven CCS technology by demonstration of more LSIPs and optimization of the system integration and standardization of the components to speed up technology learning and cost reduction. During the period, the proved technology in pure stream and power generation sectors could also be tailored into some industry processes as steel and cement and biomass sector for pilot test and field demonstration. The 2020–2030 period marks the comprehensively speeding-up deployment of CCS in the U.S. and China and the dissemination of the technology to other countries (especially other emerging economies).

5.4. The benefits of the cooperation

This cooperation model has been designed with the assumption that the U.S. and China both stand to gain more through collaboration than through independent pursuit of CCS. Besides, there is huge spillover effect on the global CCS deployment. In this section, we will summarize the benefits in not only the U.S. and China, but also the global perspective.

5.4.1. Benefits to the U.S.

The strategic benefits, as we justify the rationality for the U.S.–China CCS cooperation, are multiple. They include strengthening the U.S. energy independence, enhancing U.S. leadership on clean energy innovation, and in the long run, facilitating a secure energy future for the U.S. Because of the difficulty of quantifying them, in this section, we will focus the practical benefits, including more rapid deployment, job creation and lower costs.

- Accelerate U.S. technology:
  American expertise in CCS is well developed and significant portion is ready to be immediately applied. Cooperation between the two countries would accelerate the market penetration of the U.S. technology. Conducting initial sequestration projects using

Table 11
Key milestones and priority area of the U.S.–China CCS cooperation.

Period	Key milestones	Priority area in the U.S.	Priority area in China
2011–2015	• Agreement upon long-term vision of CCS cooperation and implementation plan • Demonstration of 2–3 LSIPs (5 ~ 6 Mt CO_2/yr) in pure streams sector • Demonstration of 2 LSIPs (3–4 Mt CO_2/yr) in new IGCC-CCS power plant (> 300 MW) • Retrofitting 1 existing power plant using post-combustion capture technology (1 Mt CO_2/yr) • Basic R&D and pilot test on oxy-combustion and other novel capture technologies • Standardization of CCS technology in pure streams sector	• Demonstration of 1 new IGCC-CCS power plant • Basic R&D and pilot test on oxy-combustion and other capture technologies • Standardization of CCS technology in pure streams sector and system integration • Standardization on geological storage modeling • Regulation protocol of CCS projects	• Demonstration of 2 ~ 3 LSIPs in pure streams sector • Retrofitting one existing power plant to test the technological feasibility • Application R&D and pilot test of oxy-combustion technology • System engineering and provision of CCS system in pure streams sector • Reduce CCS system cost in pure streams sector by 8–10% • Finishing storage capacity assessment and transportation pipeline network study by sink–source analysis
2016–2020	• Deployment of 40–50 LSIPs (80–100 Mt CO_2/yr) in matured sectors with available technology • Commercialization of IGCC capture power plant • Demonstration project of oxy-combustion technology in large-scale power plant (> 300 MW) • R&D and pilot test of oxy-combustion technology in industry process (cement, steel) • R&D and pilot test of hydrogen combustion with high efficient CCGT • R&D and pilot test of capture technology in biomass combustion power plant • Creation of CDM-like mechanism for CCS deployment	• Prove the technological feasibility of large-scale post-combustion technology in both new and retrofitting power plant • R&D and pilot test of oxy-combustion technology in industry process (cement, steel) • R&D and pilot test of hydrogen combustion with high efficient CCGT • R&D and pilot test of capture technology in biomass combustion power plant • Deployment of 15–20 LSIPs with proved technology	• Deployment of 30–35 LSIPs with matured technology (pure streams, IGCC-CCS) • Construction of regional CO_2 transportation networks • Reduce the cost of proven technology (pure stream and IGCC-capture) by 8–10% by learning-by-doing and better optimization • Demonstration of oxy-combustion in one large-scale power plant (> 300 MW)
2020–2030	• Large-scale deployment of LSIPs (800 Mt–1 Gt CO_2/yr) • Commercialization of large-scale power plant oxy-combustion technology • Demonstration and deployment of oxy-combustion technology in industry process (cement, steel) • Demonstration and deployment of hydrogen combustion with high efficient CCGT • Demonstration and deployment of capture technology in biomass combustion power plant • Creation global carbon market for CCS deployment	• Prove the technology of oxy-combustion technology in industry process (cement, steel) • Prove the capture technology in biomass combustion power plant • Prove the technology of hydrogen combustion with high efficient CCGT • Deployment of 100–120 LSIPs with proved technology	• Demonstration the technology of oxy-combustion technology in cement and steel industry • Deployment of 300–350 LSIPs with proved technology • Construction national CO_2 transportation networks • Reduce the proven capture technology by another 15–20%

the high-purity CO_2 streams more readily available in China will allow both sides to benefit from the faster execution and lower costs that China offers. Proving technologies as quickly as possible is critical to accelerate development of cost assessments, technical findings, risk profiles, and regulatory frameworks. The working knowledge of CCS practices and protocols gained from initial demonstrations in China would also be available to the U.S. and would help to accelerate the deployment of CCS in the U.S. by 5–10 years, with benefits to companies in related sectors.

- Create U.S. jobs:
By taking advantage of U.S. technology and heavy equipment purchases and testing, projects in both the U.S. and in China would help to improve the competitiveness of U.S. firms in a global market, while creating jobs in the U.S. Although China is developing some cutting-edge technology in this field, a significant amount of the most advanced technology would logically end up being exported to China to supply its CCS market. Such collaborative projects would also spur U.S. domestic job growth again through acceleration of wide-scale deployment of CCS technology. The IEA estimates show that in a baseline scenario, the CCS sector would create 127,000 direct and indirect net new jobs in the U.S. by 2022. A five-year acceleration increases that to 430,000 in 2022, while a10-year acceleration gets 943,000 in 2022 [3].
- Lower U.S. electricity prices:
As CCS is increasingly viewed as a critical part of global carbon abatement efforts, the acceleration of the development of the technology could yield significant reductions in the ensuing electricity rates. CCS collaboration would add value by reducing CCS costs and thus ensuring electricity rates remain lower than might otherwise be the case. The IEA estimate that five-year acceleration through cooperation with China would save U.S. $5 billion on electricity bill and ten-year acceleration would save U.S. $18 billion on electricity bill.
- Direct cost savings:
Several key components of CCS are cheaper in China than in the United States. These include steel, cement, labor, and the savings from more rapid project completion. Focused joint effort could therefore reduce the cost of individual retrofit projects and construction time by as much as 50%.

5.4.2. *Benefits to China*

The cooperation will provide China with lots of strategic benefits as securing energy security and supply in the long-term, enhancing the economic competiveness by participating in clean energy market, easing the international pressure on climate change and thus helping creating a favorable environment for its rise. The practical benefits will include enhancing Chinese expertise and expanding its share on CCS market, expanding cooperation on other clean energy technology, sharing risk on CCS deployment, and facilitating the realization of its 2020 GDP carbon intensity target.

- Increase Chinese CCS expertise:
U.S.–China cooperation will provide China with access to new advanced CCS technology, so it too stands to gain the requisite expertise to become more competitive in a burgeoning future green technology market. In the global labor division, China will certainly gain more from provision of the CCS technology by manufacturing equipment and providing engineering service.
- Facilitate additional collaboration in preferred Chinese areas:
Collaborating with the U.S. on CCS will give China more political capital to press for collaborative efforts in other preferred areas, such as technology transfer and investment in the fields of renewable energy and energy efficiency, where the U.S. holds leading edge and China appeals for even closer cooperation with the U.S.
- Risk sharing and cost reduction:
According to various study, China will be the country where most of the CCS projects will be deployed. By combining resources, China can share the risks of failure with the U.S. instead of bearing such risks separately. Besides, with the closer cooperation with the U.S., the accelerated cost reduction will also reduce the electricity bill for China.
- Facilitation of China's 202 GDP carbon intensity target:
China has pledged to the international society to decrease its GDP carbon intensity by some 40–45% at 2020 as of 2005 level and has actively engaged in realizing the target. Energy efficiency and development of non-fossil energy alone will not be enough to realize the target, especially if the economic growth rate is faster than planned, which happened at the last three FYP periods. A closer cooperation with the U.S. would thus facilitate the deployment of CCS in China and facilitate the realization of China's 2020 carbon intensity target. What is more important, collaborating with the United States as partner to help solve one of the world's most ominous crises would give China an unparalleled opportunity to assume global leadership. Such leadership would possibly shape China's new position on climate change policy.

5.4.3. *Benefits to the world as a whole*

- Promote global learning and reduce global deployment cost:
A closer U.S.–China cooperation will utilize the comparative advantages of both the U.S. and China on the value chain of CCS technology and promote global learning on the technology. Given China's successful experience on cost reduction in wind turbine and solar panel by technology learning (learning by doing and learning by using), the active role of China could bring down the cost of CCS in a significant factor and reduce the deployment cost.
- Make rapid emissions reductions possible:
If the priority area envisioned in the study is implemented, the near-term cooperation could result in the indefinite storage of nearly 10 million tons of CO_2 (which would otherwise enter the atmosphere) each year beginning two to five years after project initiation. The medium-term cooperation could result in the indefinite sequestration of 100 Mt of CO_2 at around 2020 and would catalyze the rapid global deployment.
- Provide financial sureness in the market:
The closer U.S.–China cooperation would create standards for safe, cost-effective deployment project, in turn it will give the financial community the confidence and tools for investments in ongoing emissions reduction projects in both countries.
- Provide needed leadership on global climate change:
The global climate crisis demands bold leadership, new partnerships and the transition to a low-carbon economy. A stronger U.S.–China cooperation will definitely provide the imperative leadership to the international society and help shape the global climate change policy for post-Kyoto era.

6. Possible hurdles and discussions

Even though a closer and stronger U.S.–China cooperation on CCS deployment is beneficial not only to two countries but also to the world as a whole, there are many possible hurdles that the political leaders in both countries must recognize and address properly to make the cooperation possible.

On the U.S. side, while support for action on climate change is growing, substantial obstacles still persist. A complicating factor

in the CCS debate is the United States' relationship with the major carbon emitting countries in the developing world, especially those with whom it has a competitive trade relationship. Many Americans and their representatives refuse to support a price on carbon or mandatory emissions reductions for fear of creating a competitive disadvantage for the U.S. Given the existing political climate in the U.S., any collaboration with China will have to navigate a number of barriers to overcome such fears.

Congress will most likely oppose the use of U.S. tax dollars to fund collaborative projects in China unless they bring substantial co-benefits to American workers [3]. The U.S. trade deficit with China and its continued reliance on Beijing to finance U.S. budget deficits are topics that tend to dominate the bilateral economic relationship. The fact that the Chinese economy is recovering more quickly from the global financial crisis than that of the U.S. reinforces a perception of those imbalances and creates further resistance against funding collaborations.

The U.S. Congress's historic relationship with developing nations on climate change has been competitive and apprehensive. When the Clinton administration brought back the Kyoto Protocol to the Congress, the Senate responded with the 1997 Byrd-Hagel Resolution, which defiantly proclaimed that there would be no ratification of any international climate treaty that failed to include defined emissions commitments from developing countries, something not called for in the Protocol itself. The House also passed the Foreign Relations Authorization bill (H.R. 2410) in 2009, which included a specific provision requiring the State Department to ensure that international treaties do not weaken U.S. companies' intellectual property rights. What is more, the 2009 ACES Act included provisions that would essentially enact border tax adjustments on imports from countries that fail to implement legally binding controls on their greenhouse gas emissions.

To address the possible opposition from the U.S. Congress, any cooperation protocol between two countries must strive to maintain the balance of interest of both sides carefully. It is why in the cooperation model proposed in the paper, a balanced funding support from both countries, a balanced projects allocation between research institutions and companies from both countries, a balanced involvement of stakeholders from both countries, and a considerate property rights management respecting the interests of related stakeholders are the key considerations. As a matter of fact, because of the competency of U.S. research institutions and companies, the designation plus tournament funding and projects allocation model would ensure that organizations from the U.S. side would gain more resource from the cooperation, and ultimately, gain more benefits by controlling the majority of the technology patent.

Although "clean coal" is being widely hailed by many industry groups, there is doubt on some environmentalists on the viability of large-scale sequestration, citing CCS's high cost and the lack of proven technology. The doubt has led to protests against early sequestration projects in Europe. The U.S. can expect similar opposition at home as sequestration projects begin. Besides, the "not-in-my-back-yard" attitude towards renewable energy technology in the U.S. would also be a potential barrier. We believe that the successful demonstration project in China first will eliminate the unnecessary doubt of U.S. pubic, and the participation of environmental NGOs in the networks will facilitate the effective communication with the public.

On the China side, China's primary commitment will continue to be to economic development and political stability, and it is depending on scientific innovation to reduce the environmental costs of its growth. Given China's overriding concern of economic development, it is not surprising that CCS projects are viewed with certain skepticism. Besides, because CCS is expensive, fails to diversify China's energy sources, focuses on global rather than immediate and local environmental problems, and comes with technical uncertainties and an onerous "energy penalty," China has been cautious in committing to an aggressive program in this field.

On global climate change policy negotiation, China expects developed countries to assume greater responsibility for emissions reductions. Speaking on behalf of the G77, a consortium of developing countries, China argues that since developed nations created the problem of climate change, they should inherit the primary responsibility for remedying it. For example, China has called on developed countries to contribute 0.5–1% of their GDP to set up a global clean technology fund, helping developing nations reduce their emissions. From the perspective of developed countries, it is unlikely to happen. Therefore any prospective CCS collaboration must recognize China's underlying priorities of economic development and energy security, and successfully address the challenges of costs and other uncertainties in deployment. Hence one of the key elements is cooperation between two countries on global climate policy. We believe that the joint-hand of the U.S. and China will certainly speed up the icebreaking of the current deadlock on climate negotiation.

However, there are reasons to believe that various Chinese stakeholders would be receptive to collaborative overtures in the field of CCS, especially if these overtures are made with the right incentives and with the U.S. explicitly taking responsibility for its fair share of the historic burden. Demonstrating and developing CCS technology could also help establish China as a leader in innovation, technology and climate change mitigation efforts. Therefore, providing that the CCS cooperation between the U.S. and China is actually based on equality and mutual benefit, the cooperation will definitely be in the interest of China. To back up our point, we cite a most recent speech from China Vice Premier Li Keqiang, in a dialogue with U.S. Secretary of Energy Steven Chu when Chu was visiting Beijing at 21 September 2011.

> *"As the world's major energy producers and consumers, China and the United States enjoy a broad consensus in maintaining the stability of global energy market. The two countries should seize opportunities to define future cooperation, set up a long-term cooperation mechanism and facilitate bilateral cooperation in researching clean and renewable energy, as well as advanced energy technology."*

7. Concluding remarks

Global GHG emissions are fast approaching unsustainable and alarming levels. It is increasingly evident that maintaining the current trajectory of GHG emissions poses wide-ranging and potentially catastrophic risks to natural systems and human welfare. It is also clear that an unprecedented level of global cooperation will be necessary to successfully confront the immense challenge of reversing the effects of climate change.

The global nature of climate change demands new forms of partnerships. These partnerships are necessary to accelerate CO_2 emissions reductions and the transition to a low-carbon economy, and do so while producing tangible and near-term benefits for all parties involved. The United States and China are the world's largest GHG emitters. Collaboration between the two nations, therefore, offers the greatest opportunity for achieving meaningful reductions in global greenhouse gas emissions. One critical pathway for collaboration specifically identified in the United States and China's recent joint commitments is CCS, which has the potential to mitigate emissions from coal-fired power plants and other stationary industry facilities. The United States and China's

continued reliance on coal-fired power to generate electricity is a reality that must be addressed in any comprehensive climate change policy.

Currently, China and the U.S. are cooperating on CCS through the mechanism of CERC based on the U.S.–China Strategic Forum on Clean Energy Cooperation. It is a beginning of a new era of clean energy cooperation between the two countries, but should not be the final destination. In this paper, we justify the rationality for a closer and stronger U.S.–China cooperation on CCS, with rapid global deployment as the ultimate target. We brainstorm the possible cooperation model, discuss the key elements of the model, expound the benefits of the cooperation and address the possible hurdles from both sides and the solutions to them. The model and the specific milestone discussed in the paper can provide concrete basis for the two nations on negotiation of long-term stronger CCS cooperation. Because the negotiation process is bound to be difficult because of the difference in national interests and the existence of hurdles from two sides, the political leaders' long-term vision and wise is important in steering the negotiation.

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